APTIC # 20877

0939

PB 207 850

AN INVESTIGATION OF DIESEL POWERED VEHICLE ODOR AND SMOKE

PART II

for

Automotive Research and Development Section
National Center for Air Pollution Control
Contract No. PH 86-67-72
Public Health Service
Department of Health, Education and Welfare

FINAL REPORT

Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228

February 1968

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield, Va. 22151

156

No. AR-644

Vehicle Emissions Research Laboratory

AN INVESTIGATION OF DIESEL POWERED VEHICLE ODOR AND SMOKE

PART II

Karl J. Springer

Details of illustrations in
this document may be better
studied on microfiche

for

Automotive Research and Development Section
National Center for Air Pollution Control
Contract No. PH 86-67-72
Public Health Service
Department of Health, Education and Welfare

FINAL REPORT

Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228

February 1968

Reviewed:

John M. Clark Jr.

John M. Clark
Department Director

Approved:

Henry J. Korp

Henry Korp, Vice President
Engines, Fuels, and Lubricants Division

FOREWORD

This project, Part II of a long-range investigation of diesel powered vehicle odor and smoke, was initiated by the Automotive Research and Development Section, National Center for Air Pollution Control, United States Public Health Service, Department of Health, Education and Welfare, 5710 Wooster Pike, Cincinnati, Ohio. The engineering effort upon which this report is based was accomplished by Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas, under Contract U.S. PHS PH 86-67-72 entitled "An Investigation of Diesel Powered Vehicle Odor and Smoke - Part II." The author, Mr. Karl J. Springer, was the Project Leader of the research and development work. This program started on January 15, 1967 and was completed February 15, 1968.

The Project Officer cognizant of this program was Mr. George D. Kittredge, Deputy Chief, Automotive Research and Development Section, Emissions Control Research and Development Program, National Center for Air Pollution Control, U.S. Public Health Service, Department of Health, Education and Welfare, 5710 Wooster Pike, Cincinnati, Ohio 45227. This project was identified within Southwest Research Institute as No. 11-2056-01.

ABSTRACT

Continuing Part I of the long-range investigation of diesel powered vehicle odor and smoke, the Part II program was concerned with the effectiveness of various methods of reduction and control of diesel emissions. To this end, the diesel emissions measurement facilities, procedures, and conditions established, developed and identified during the Part I program were employed. The SwRI, ten-person odor panel, trained and experienced in the characterization of dilute diesel exhaust samples according to the PHS quality/intensity rating kit and the PHS full-flow, light-extinction smokemeter, were exclusively used to measure odor and smoke, respectively. An evaluation of several two-cycle powered municipal buses equipped with automotive type catalytic devices revealed that one device noticeably reduced exhaust odor and certain other emissions such as formaldehyde, total aldehydes, and acrolein. Although the catalytic device had no positive effect on smoke, it did possess an excessive sound level in the single configuration evaluated. A 6-month evaluation of the smoke suppressing ability of a commercially available barium diesel fuel additive in a five-truck fleet was successful in demonstrating the effectiveness of this technique for smoke reduction over an extended period. Engine derating was investigated for its effect on exhaust odor and smoke with a Cummins NH-220, GM 6-71 N and a Mack END-673P. Although engine power rating was found to have a pronounced effect on visible smoke output, power rating appeared to have little or no effect on perceived odor. A limited study of the effect of injecting air in the exhaust at the underside of exhaust valves of a two-cycle powered municipal bus had a negligible effect on odor and smoke. A brief evaluation of the effect of the Jacobs engine brake on the odor and smoke from another two-cycle powered bus also resulted in no noticeable change. A variety of small evaluations and special studies was conducted and reported, including the effect of exhaust pipe size on smoke readings, preliminary studies of a tentative PHS smoke procedure, attempted evaluation of an electrostatic precipitator, and base line odor, smoke, and emissions from a municipal coach powered by a four-cycle V8 engine. The results of a preliminary feasiblity study and experimental evaluation of an instrumental method for possible diesel odor rating and correlation to the human odor panel method is discussed. Recommendations offered include a development and proof test program of an instrumental technique for odor measurement and correlation with the human odor panel. Also recommended are long-range fleet tests of both catalytic devices and fuel additives including screening type evaluations of additional devices and additives as they become available, and acquisition of additional base line data for a variety of diesel powered vehicles.

BIBLIOGRAPHIC DATA SHEET	1. Report No. APTD-0939	2.	3. Recipient's Accession No.

4. Title and Subtitle

An Investigation of Diesel Powered Vehicle Odor and Smoke - Part II

5. Report Date

February 1968

6.

7. Author(s)

Karl J. Springer

8. Performing Organization Rept. No. AR-644

9. Performing Organization Name and Address

Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228

10. Project/Task/Work Unit No.

11. Contract/XXXX No.

PH 86-67-72

12. Sponsoring Organization Name and Address

Department of Health, Education, and Welfare
Public Health Service
National Center for Air Pollution Control
Automotive Research and Development Section

13. Type of Report & Period Covered

Final

14.

15. Supplementary Notes

16. Abstracts

A ten-person odor panel, trained in the characterization of dilute diesel exhaust samples according to the PHS quality/intensity rating kit and the PHS light-extinction smokemeter, were used to measure odor and smoke. Evaluation of several two-cycle powered municipal buses equipped with automotive type catalytic devices revealed that one device noticeably reduced exhaust odor and other emissions such as formaldehyde, total aldehydes, and acrolein, but had no positive effect on smoke. The smoke suppressing ability of a barium diesel fuel additive was successfully demonstrated in a five-truck fleet. Power rating had a pronounced effect on visible smoke output, although it appeared to have little or no effect on perceived odor, when engine derating was investigated with a Cummins NH-220, GM 6-71 N and A Mack END-673P. A limited study of the effect of injecting air in the exhaust at the underside of exhaust valves of a two-cycle powered municipal bus had a negligible effect, while a brief evaluation of the Jacobs engine brake also resulted in no noticeable change. Special studies were conducted and reported including the effect of exhaust pipe size on smoke readings, preliminary studies of a tentative PHS smoke procedure, attempted evaluation of an electrostatic precipitator, and base line odor, smoke, and emissions from a municipal coach powered by a four-cycle V8 engine.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Exhaust emissions
Odors
Smoke
Particles
Diesel engines
Buses (vehicles)
Motor trucks
Odor detection
Measurement
Electrostatic precipitator
Catalytic converters
Fuel additives
Acroleins
Formaldehyde
Aldehyde
Barium inorganic compounds
Odor control

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 13B

18. Availability Statement Unlimited	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 156
	20. Security Class (This Page) UNCLASSIFIED	22. Price

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS vii

LIST OF TABLES x

I. INTRODUCTION 1

- A. Part I Program Review 1
- B. Objective and Approach 1
- C. Coordinating Research Council Visit 2
- D. Nomenclature 2

II. DESCRIPTION OF FACILITY, EQUIPMENT, AND FUELS 4

- A. Diesel Emissions Measurement Facility 4
  - 1. Review of Part I Methods and Facilities 4
  - 2. Part II Facility Improvements 8
- B. Equipment and Instruments 11
- C. Description of Fuels 12

III. STUDY OF ENGINE DERATING ON ODOR AND SMOKE 15

- A. GM Detroit Diesel Division 6-71 N Engine Results 15
- B. Cummins NH-220 Engine Results 19
- C. Mack END-673P Engine Results 22
- D. Summary 26

IV. FLEET TEST OF SMOKE SUPPRESSANT ADDITIVE 27

- A. Preparations 27
- B. Results 28
- C. Summary 31

V. EFFECT OF DIESEL EXHAUST MANIFOLD OXIDATION ON ODOR AND SMOKE . . 32

- A. Preparations 32
- B. Results 36
- C. Summary 39

VI. EFFECT OF JACOBS ENGINE BRAKE ON ODOR AND SMOKE 40

- A. Preparations 40
- B. Results 40
- C. Summary 44

VII. CATALYTIC MUFFLER EVALUATION 45

- A. Code "X" Catalytic Muffler Device Evaluation 47
  - 1. Catalytic Device Code "X"-1 Results 49
  - 2. Catalytic Device Code "X"-2 Results 60
  - 3. Catalytic Device Code "X"-3 Results 67
  - 4. Summary of Code "X" Muffler Evaluation 75

Reproduced from
best available copy.

TABLE OF CONTENTS (Cont'd)

Page

B. Code "Y" Catalytic Muffler System Evaluation 76

1. Catalytic Reactor System Code "Y" Results 77
2. Summary 84

VIII. CHEMISTRY STUDIES 86

A. Exhaust Chemistry 86
B. Odor Correlation Chemistry 90

1. Initial Familiarization 90
2. Sampling and Sample Preparation 93
3. GC Column and Operational Requirements 101
4. Summary 102

IX. VARIOUS DIESEL EMISSIONS MEASUREMENTS 104

A. Effect of Exhaust Pipe Diameter on PHS Smokemeter Readings 104
B. Preliminary Studies with the Tentative PHS Smoke Test Procedure 107
C. Evaluation of Gordine Diesel Electrostatic Precipitator 112
D. Odor, Smoke, and Exhaust Emissions from a Flxible Coach Powered by a Cummins Four-Cycle Engine 114

1. Preparations 114
2. Results 116
3. Summary 121

X. DATA ANALYSIS AND STATISTICAL SUPPORT 122

A. Treatment of Odor Panel Data 122
B. Selection of "U" Statistic to Determine Difference 123
C. Correlation Studies 125

1. Description of Computer Program 125
2. Results 126
3. Summary 131
4. Description of Future Correlation Experiment 131

XI. SUMMARY 133

XII. CONCLUSIONS AND RECOMMENDATIONS 136

LIST OF REFERENCES 139

APPENDIXES 141

LIST OF ILLUSTRATIONS

Figure | Page

1 U.S. Public Health Service Quality/Intensity Kit for Characterization and Evaluation of Diesel Exhaust Odor 5
2 U.S. Public Health Service Smokemeter 5
3 Isometric View of Odor Facility 6
4 Odor Panel and Exposure Facility for Simultaneous Evaluation of Diluted Sample Odor Quality/Intensity 7
5 Special SwRI Laboratory Road Simulation Facility 8
6 Special SwRI Chassis Dynamometer and Vehicle Inertia Simulation Equipment . . . 9
7 U.S. Public Health Service Smokemeter Mounted on Extended GM Municipal Bus Exhaust Pipe 9
8 Truck-Tractor Prepared for Smoke Evaluations with U.S. Public Health Service Smokemeter Mounted 10
9 Tandem Drive Axle Truck-Tractor under Odor Evaluation 10
10 Right or Rear Bank of Detroit Diesel 6V-71 E Engine Equipped with Exhaust Manifold Oxidation (DEOX) System (1/4-In. Injection Tubes, One per Cylinder) 33
11 Left or Front Exhaust Manifold Removed Showing the Length and Position of DEOX Air Delivery Tubes (1/4-In. Injection Tubes, One per Cylinder) 33
12 Left or Front Bank of Detroit Diesel 6V-71 E Engine Equipped with Exhaust Manifold Oxidation (DEOX) System (3/16-In. Injection Tubes, One per Each Valve of Each Cylinder) 34
13 Left or Front Exhaust Manifold Removed Illustrating the Length and Position of DEOX Air Delivery Tubes (3/16-In. Injection Tubes, One per Each Valve of Each Cylinder) 35
14 Air Delivery Equipment and PHS Smokemeter used during Exhaust Manifold Oxidation (DEOX) Experiments (Connected to Left or Front Bank of Detroit Diesel 6V-71 E Engine) 35
15 Engine Compartment of GM Coach Powered by Detroit Diesel 6V-71 Engine . . . 41
16 Dynamic Sampling and Dilution System for Vehicle Exhaust Odor Determination . 46
17 End View of Catalytic Device Code "X". 48
18 Cutaway View of Catalytic Device Code "X" 48
19 Catalytic Device Code "X" Installed under Coach 49
20 Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 681, Date: August 9 and 10, 1967). 51

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page
21	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 681, Date: September 13 and 14, 1967)	51
22	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 681, Date: October 17 and 18, 1967)	52
23	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 678, Date: August 16 and 17, 1967)	62
24	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 678, Date: October 11 and 12, 1967).	62
25	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 768, Date: August 23 and 24, 1967)	69
26	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 768, Date: September 26 and 27, 1967)	69
27	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 768, Date: November 1 and 2, 1967).	70
28	Catalytic Device Code "Y" Exhaust System.	77
29	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 678, Date: September 6 and 7, 1967)	79
30	Overall Comparison of Diesel Odor Evaluation with and without Catalytic Muffler Installed (Bus 768, Date: November 7 and 8, 1967)	79
31	Code "Y" Catalytic Diesel Exhaust Reactors (Removed after 1979 Test Miles and 17 Test Days)	84
32	Sampling and Wet Collection Glassware and Apparatus for Exhaust Emissions from Diesel Powered Vehicles	89
33	Partial View of Glassware and Apparatus Employed for Analysis of Wet Collected Diesel Exhaust Samples	89
34	Schematic Flow Diagram of Possible Odor Panel--Instrument Correlation Technique.	94
35	Instrument--Subjective Analysis Odor Correlation--Pilot Study.	96
36	Typical Gas Chromatogram of Diesel Exhaust	97
37	Typical Gas Chromatogram of Diesel Exhaust after Passing through Three Cold Traps in Series at -75°C	97
38	Typical Gas Chromatogram of Diesel Exhaust after Passing through Three Cold Traps in Series at -35°C	98
39	Typical Gas Chromatogram of Water Collected Exhaust Odorants from Laboratory Two-Cycle Engine	102

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page
40	Schematic of Test Apparatus and Arrangement used for Evaluation of the Gordine Diesel Exhaust Precipitator	112
41	Gordine Diesel Exhaust Electrostatic Precipitator after 5 Min of Operation with a Multicylinder Truck Diesel Exhaust (Flow is from Right to Left)	114
42	Flxible Transit Coach on Test in High Bay Chassis Dynamometer Area of Vehicle Emissions Research Laboratory	115
43	Rear View of Flxible Coach Powered by Cummins V8-265, Four-Cycle Engine	116

LIST OF TABLES

Table Page

1 Commercial Diesel Fuel Specifications--Typical 12

2 Inspection of Commercial Number 1 and Number 2 Diesel Fuels used in Part II Program 13

3 Overall Summary of the Effect of Derating a Detroit Diesel 6-71 N Powered Truck-Tractor on Exhaust Smoke 19

4 Overall Summary of the Effect of Derating a Cummins NH-220 Powered Truck-Tractor on Exhaust Smoke 21

5 Overall Summary of the Effect of Derating a Mack END-673P Powered Truck-Tractor on Exhaust Smoke 25

6 Fleet Test Vehicle Mileage Data (End of 6 Months of Operation) 28

7 Overall Summary of Smoke Inspection Results for Fleet Test of Smoke Suppressant Additive 29

8 Comparison of Odor Evaluations with and without Diesel Exhaust Manifold Oxidation (DEOX) System Operative 37

9 Effectiveness of Exhaust Manifold Oxidation (DEOX) on Visible Exhaust Smoke from a Two-Cycle Powered Bus 38

10 Overall Summary of Initial and Final Odor Panel Responses with and without Jacobs Brake Operative 42

11 Overall Summary of Initial and Final Smoke Readings with and without the Jacobs Brake Operative 43

12 Catalytic Muffler Evaluation Schedule 45

13 Overall Summary of Odor Evaluations Catalytic Muffler "X"-1 vs Stock Muffler 50

14 Odor Response U_s Statistical Analysis Summary Catalytic Muffler Code "X"-1 vs Stock Muffler 54

15 Overall Summary of Smoke Evaluations Catalytic Muffler "X"-1 vs Stock Muffler 55

16 Summary of Average "As-Measured" Exhaust Emissions and Muffler Pressure and Temperature Measurements Catalytic Muffler Code "X"-1 vs Stock Muffler 56

17 Exhaust Emissions U_s Statistical Analysis Summary Catalytic Muffler Code "X"-1 vs Stock Muffler 58

18 Overall Summary of Odor Evaluations Catalytic Muffler "X"-2 vs Stock Muffler 61

19 Odor Response U_s Statistical Analysis Summary Catalytic Muffler Code "X"-2 vs Stock Muffler 63

LIST OF TABLES (Cont'd)

Table Page

20 Overall Summary of Smoke Evaluations Catalytic Muffler "X"-2 vs Stock Muffler . . . 64

21 Summary of Average "As-Measured" Exhaust Emissions and Muffler Pressure and Temperature Measurements Catalytic Muffler Code "X"-2 vs Stock Muffler. . . . 65

22 Exhaust Emissions U_s Statistical Analysis Summary Catalytic Muffler Code "X"-2 vs Stock Muffler . . . 66

23 Overall Summary of Odor Evaluations Catalytic Muffler "X"-3 vs Stock Muffler . . . 68

24 Odor Response U_s Statistical Analysis Summary Catalytic Muffler Code "X"-3 vs Stock Muffler. . . . 71

25 Overall Summary of Smoke Evaluations Catalytic Muffler "X"-3 vs Stock Muffler. . . . 72

26 Summary of Average "As-Measured" Exhaust Emissions and Muffler Pressure and Temperature Measurements Catalytic Muffler Code "X"-3 vs Stock Muffler. . . . 73

27 Exhaust Emissions U_s Statistical Analysis Summary Catalytic Muffler Code "X"-3 vs Stock Muffler . . . 74

28 Overall Summary of Odor Evaluations Catalytic Muffler Code "Y" vs Stock Muffler. . . . 78

29 Odor Response U_s Statistical Analysis Summary Catalytic Muffler Code "Y" vs Stock Muffler. . . . 80

30 Overall Summary of Smoke Evaluations Catalytic Muffler Code "Y" vs Smoke Muffler. . . . 81

31 Summary of Average "As-Measured" Exhaust Emissions and Muffler Pressure and Temperature Measurements Catalytic Muffler Code "Y" vs Stock Muffler . . 82

32 Exhaust Emissions U_s Statistical Analysis Summary Catalytic Muffler Code "Y" vs Stock Muffler . . . 83

33 Results of Pilot Study of the Effect of Fuel Portions on Exhaust Odor. 92

34 Results of Pilot Study of the Effect of Fuels and Fuel Blends on Exhaust Odor . . 92

35 Diesel Exhaust Mass Spectrometric Analysis . . . 95

36 Small Panel Evaluation of Precolumn Effectiveness on Odor Removal 99

37 "Precolumn" Hydrocarbon Separation Efficiency . . . 101

38 Gas Chromatograph Column Dimensions and Packing Proposed for use in Reevaluation of Water Absorbed Diesel Exhaust . . . 101

LIST OF TABLES (Cont'd)

Table		Page
39	Summary of PHS Smokemeter Readings vs Pipe Size and Exhaust Flow.	106
40	DC Power Input to Gordine Diesel Exhaust Electrostatic Precipitator	113
41	Overall Summary of Odor Evaluations from Flxible Bus.	117
42	Summary of Smoke Measurements Obtained with Flxible Coach.	119
43	Summary of "As-Measured" Average Flxible Coach Exhaust Emissions Measurements	120
44	Statistical Correlation Study of Diesel Odor and Emissions List of Variables, Their Mean and Standard Deviation	127
45	Statistical Correlation Study of Diesel Odor and Emissions Correlation Matrix .	127

I. INTRODUCTION

Emissions from diesel powered vehicles continue to be the object of increased government and industrial concern. A long-range investigation of diesel powered vehicle odor and smoke, sponsored by the U.S. Public Health Service, began at Southwest Research Institute's Vehicle Emissions Research Laboratory in February 1966. Part I of this long-range investigation was completed in February 1967. The Southwest Research Institute diesel studies were part of the overall Public Health Service program and were coordinated with those under way at the Petroleum Research Center, U.S. Bureau of Mines, and at Scott Research Laboratories. Prior to introducing the objective and approach of the Part II work described and discussed in this report, it may be helpful to briefly review the Part I program and results. Attention is also called to the change in smoke reading nomenclature as well as the April 1967 visit of the Diesel Emissions Group of the Coordinating Research Council.

A. Part I Program Review

The initial year of program effort, completed in February 1967, was concerned with noticeable levels of diesel smoke and odor both from two-cycle powered city buses and four-cycle powered intercity trucks. The program included field studies, development of facilities and procedures, study of vehicle variability, and investigation of two techniques for smoke reduction. The field studies were conducted to determine: (1) operating conditions that produce significant levels of odor and smoke, and (2) the level of atmospheric exhaust dilution that a motorist or pedestrian might experience behind a bus or truck. Results of the field studies indicated that the two-cycle powered bus odor and smoke were grossly different from the four-cycle powered truck. Reasonable atmospheric dilution levels from a typical horizontal bus exhaust were found to range from 100:1 to 1000:1, whereas the dilution levels from a vertical exhaust stack equipped truck ranged from 700:1 to 7000:1.

These results permitted realistic simulation of field operation in a specially designed laboratory odor and smoke measurement facility. Newly developed Public Health Service smoke and odor measurement methods were employed in this facility. The odor measurement method involved simultaneous exposure of a panel of ten persons to a diluted sample of diesel exhaust. A diesel odor evaluation kit, composed of an overall diesel odor and four different qualtities at various intensities, was used as a reference by the panel. Smoke was measured by means of a PHS smokemeter under both constant speed and accelerating type vehicle conditions. Utilizing these measurement methods, chassis dynamometer, panel, and smokemeter procedures were developed for the city bus (five odor and six smoke conditions) and for the intercity tractor (six odor and seven smoke conditions). The trained panel was able to relate the effect of dilution, load, and other operating parameters to the quality/intensity of the dilute sample.

These conditions and procedures were then employed to measure the smoke and odor variability from ten similar buses and ten similar trucks. Limited investigations of fumigation and dilution (two proposed methods for reducing smoke) resulted in only a partial or technical success. For complete results and discussion of the Part I studies, please refer to the comprehensive final technical report entitled "An Investigation of Diesel Powered Vehicle Odor and Smoke - Part I" (Ref. 1)* dated March 1967 under Contract PH 86-66-93. A brief summary of the preparations phase for the Part I program as well as program objectives may be found in a paper presented at the National Petroleum Refiners Fuels and Lubricants Meeting in Philadelphia in September 1967 (Ref. 2).

B. Objective and Approach

The objective of the Part II program was to continue to provide assistance to the Public Health Service in the development of engineering data regarding emissions from diesel powered vehicles. Specifically, this follow-on program was intended primarily to determine the effectiveness of a number of different control techniques on odor, smoke, and other emissions. A primary objective was the evaluation of available exhaust catalyst devices intended for use with two-cycle powered municipal buses, a 6-month, five-truck, fleet test of a commercial barium containing smoke suppressant fuel additive, investigation of the effect of engine derating on exhaust odor and smoke tendencies, limited studies of exhaust manifold oxidation of two-cycle exhaust by an air injection technique, and the effect of the Jacobs engine brake on odor and smoke from a two-cycle powered municipal bus. A secondary objective was to study new and novel instrumental techniques for measurement of diesel odor. Other objectives were to conduct limited studies of an electrostatic precipitator, a transit coach powered by a four-cycle, V8 diesel engine, and perform preliminary smoke measurement studies under PHS procedures.

---

*A complete list of references may be found at the conclusion of the text of this report.

The overall approach was to employ the background and experience gained during the Part I program by applying the measurement methods, operating conditions and procedures, and specialized facilities previously developed. Many of the device, additive, or technique evaluations employed simplified back-to-back type measurements in which all test parameters were held constant except for the primary test item. For example, a catalytic muffler was evaluated against the standard stock unit or an additive treated fuel was examined versus the untreated fuel with no other parameters changed. The approach, furthermore, was to measure the odor, smoke, and other emissions not once or twice but a minimum of four times under usually five or six different operating conditions. Depending on the evaluation, these sets of measurements were generally repeated, at least once and sometimes up to four times, to ensure the reliability of the data and guard against false conclusions.

To assure realistic data, buses and trucks from normal service fleets were utilized. The General Motors (GM) Truck and Coach Division Model TDH-4519 municipal buses were provided from the San Antonio Transit System, and truck-tractor units were supplied by the Howell Refining Company, Ryder Truck Leasing Company, Hertz Truck Rental, ABC Truck Rental (National Leasing Co.), and others.

C. Coordinating Research Council Visit

On April 13, 1967, members and invited guests of the Coordinating Research Council Group on Diesel Exhaust Composition were given a briefing of the past and present PHS-SwRI programs regarding diesel powered vehicle odor and smoke. In addition to this briefing, the group was given a complete tour of diesel odor and smoke measurement facilities of the Vehicle Emissions Research Laboratory, SwRI. The Diesel Exhaust Gas Group, chaired by Dr. Ernest Landen of Caterpillar Tractor, was made up of two panels; a diesel Odor Panel headed by Dr. Bill Agnew, GM Research, and the Diesel Emissions Panel led by Mr. Roy D. Quillian, Jr., Southwest Research Institute. A total of twenty-six people representing petroleum, chemical and additive industries, as well as the automotive, diesel and truck-tractor manufacturing industry, was present for the briefing and tour. Following the tour of the Vehicle Emissions Research Laboratory and observation of the SwRI odor panel evaluating samples of diluted exhaust from a two-cycle powered municipal bus, meetings were held by the CRC Odor Panel, the CRC Diesel Emissions Panel and the parent Group on Diesel Exhaust Composition.

D. Nomenclature

Throughout Part I and the majority of Part II, the term "absorbance" was employed with readings from the U.S. Public Health Service (PHS) full-flow, light-extinction smokemeter to signify the amount of reduction of the light beam due to the obscuration by the smoke plume. During a meeting with the Project Officer, Mr. George Kittredge, and Mr. Howe Hopkins, PHS, in Cincinnati on November 3, 1967, it was requested that the terminology used in describing the smoke readings with the PHS smokemeter be changed from "percent absorbance" to "percent opacity" as percent opacity more nearly described the type of readings obtained. For purposes of relating percent opacity to other measurements made and previously reported in this program in percent absorbance, 0-percent opacity is the same as 0-percent absorbance and indicates clear conditions. Also, 100-percent opacity is equivalent to 100-percent absorbance, 100-percent obscuration of the light beam.

Although obscuration, absorbance, or opacity of the smoke plume to the passage of the light beam is the parameter of direct interest, the PHS smokemeter readout meter is marked in percent transmittance. The percent opacity is defined as 100 percent minus the percent transmittance. When reference is made to the "Part I program," this means the work conducted under PHS Contract PH 86-66-93 which culminated in the March 1967 final report entitled "An Investigation of Diesel Powered Vehicle Odor and Smoke - Part I."

II. DESCRIPTION OF FACILITY, EQUIPMENT, AND FUELS

Studies of diesel exhaust emissions such as smoke, various chemical constituents, and particularly odor have been seriously restricted by the lack of specialized facilities, equipments, and instruments required for their measurement. One of the major objectives of the Part I program was to develop special facilities and systems to permit a realistic and repeatable measurement of diesel exhaust odor and smoke. Prior to the introduction of the full-flow, light-extinction type smokemeter and the concept of a subjective qualitative-quantitative characterization of exhaust odor by a trained human panel, suitable or satisfactory measurement methods for diesel odor and visible smoke were virtually nonexistent. The remainder of this section, broken into three subsections, covers: the SwRI diesel exhaust emissions facility; support equipment, instruments, and apparatus; and a description of the fuels utilized.

A. Diesel Emissions Measurement Facility

The Part II investigation was intended to apply the odor and smoke measurement methods and know-how to establish effectiveness of various diesel emissions control techniques. To accomplish this objective, the SwRI Vehicle Emissions Laboratory facilities were needed to simulate road conditions for the primary test items, diesel powered buses and trucks, as well as for the presentation and evaluation of dilute diesel exhaust odor via the SwRI odor panel. Availability of representative, two-cycle and four-cycle exhaust was also necessary from test bed operated, single and multicylinder diesel engines. Briefly reviewed and discussed in this subsection are the odor and smoke measurement methods and facilities, developed during the Part I program and utilized during the Part II program, as well as a brief description of facility refinement and additional facilities employed during Part II.

1. Review of Part I Methods and Facilities

Although a complete description of the odor and smoke measurement methods and special measurement-vehicle simulation facilities were included in the Part I Final Report (Ref. 1), it may be helpful to briefly discuss these as they were extensively employed during this program.

a. Measurement Methods

Prior to the Part I program, the U.S. Public Health Service recognized the need for odor and smoke measurement methods that would relate to what people sensorily experience as diesel exhaust odor and smoke. Under the guidance of Dr. Amos Turk, a quality/intensity (Q/I) kit comprised of a diesel composite odor and four constituent qualities diluted to various concentrations or intensities was developed. This kit of synthetic diesel-like odor qualities and intensities formed the reference against which a trained odor panel judges and rates the dilute samples of diesel exhaust. (Please refer to Ref. 3 for procedures and tests to select and train an odor panel for the evaluation of the quality and intensity of diesel exhaust.) This approach was intended to give an evaluation based on reproducible standards and was not intended as a means to ascertain levels of objectionability of diesel exhaust odor to the general public. Shown in Figure 1 is a photograph of the PHS diesel odor Q/I evaluation kit. In all, twenty-eight different odors or odor intensities are included in this kit: an overall diesel composite "D" ranging from "D"-1 to "D"-12 ("D"-12 the highest or most intense), a burnt-smoky quality "B," an aromatic-aldehydic quality "A," an oily quality "O," and a pungent quality "P," each ranging in intensity from 1 to 4, four representing the most intense. For details regarding the composition of the contents of each bottle standard, please see Reference 3.

Figure 2 is a photograph of the PHS smokemeter. The instrument measures and continuously indicates the density of the visible plume of vehicle exhaust. A light source is on one end of a collimating tube, and a photoelectric cell is located on the opposite end of the tube. The light source-collector cell assembly is placed either vertically over the usual 4-in. diameter truck stack or horizontally behind the usual 3-in. diameter bus exhaust pipe so that the light beam traverses the smoke plume issuing from the stack or pipe. The percent transmittance is then

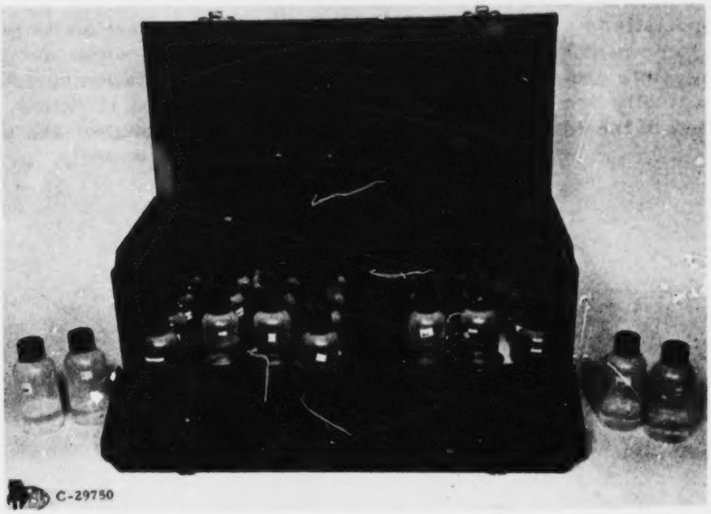


FIGURE 1. U.S. PUBLIC HEALTH SERVICE QUALITY/ INTENSITY KIT FOR CHARACTERIZATION AND EVALUATION OF DIESEL EXHAUST ODOR

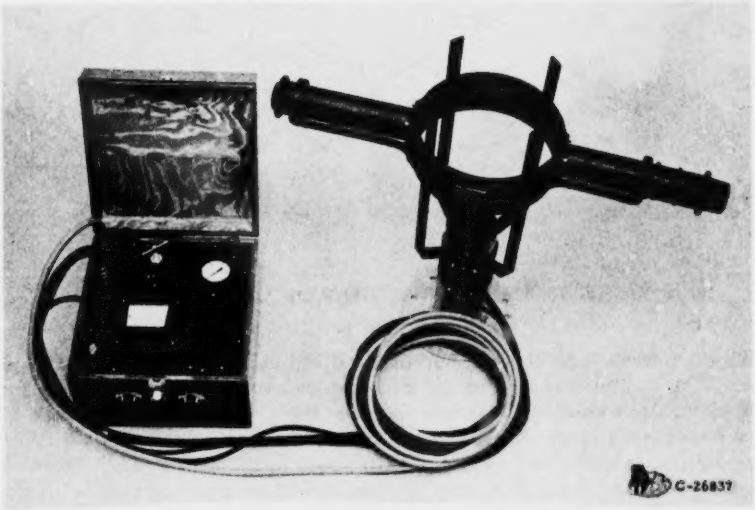


FIGURE 2. U.S. PUBLIC HEALTH SERVICE SMOKEMETER

read remotely on a meter shown in the separate instrument cabinet. The meter, intended to correspond to what the public sees, is sensitive not only to the thickness of the smoke plume but the number of smoke particles per unit volume.

b. Odor Facility

Although the odor and smoke measurement methods previously described represented a giant step forward in diesel emissions research, specialized facilities and techniques were necessary, especially to present proper samples of diesel exhaust for human panel evaluation. The design criteria to present simultaneously to a panel of ten people dilute samples of diesel exhaust under steady state cruise and transient acceleration-deceleration vehicle operation required the development of a wholly new approach in diesel odor measurement facilities. Figure 3, the overall isometric view of the odor facility, shows the general arrangement and layout of the exhaust sampling odor dilution system, and the method of handling and presenting the sample to each of the ten odor panelists. This figure also shows the close proximity of the test vehicle exhaust and chassis dynamometer road simulation equipment to the odor facility, odor room, dilution blower, etc. The sample system was designed and developed to automatically and continuously withdraw a constant mass of raw diesel exhaust regardless of temperature variations with minimum residence and hang-up (no moving parts), and without changing the character or composition of the exhaust. An automatic sample flow system comprised of a differential pressure transducer, temperature compensator, operational amplifier, square root extractor, electropneumatic convertor and flow controller was employed. The sampling system, made of stainless steel throughout, operated by the negative pressure at the inlet of the dilution blower. The dilution system may be characterized as employing the "dynamic dilution technique" to enable simultaneous presentation of the diluted sample of exhaust to members of the odor panel. As shown in the Figure 3 schematic, the raw diesel exhaust was continuously and rapidly mixed with prefiltered and deodorized (charcoal filtered) diluent air, and ducted immediately into the odor room for presentation to each of the panelists.

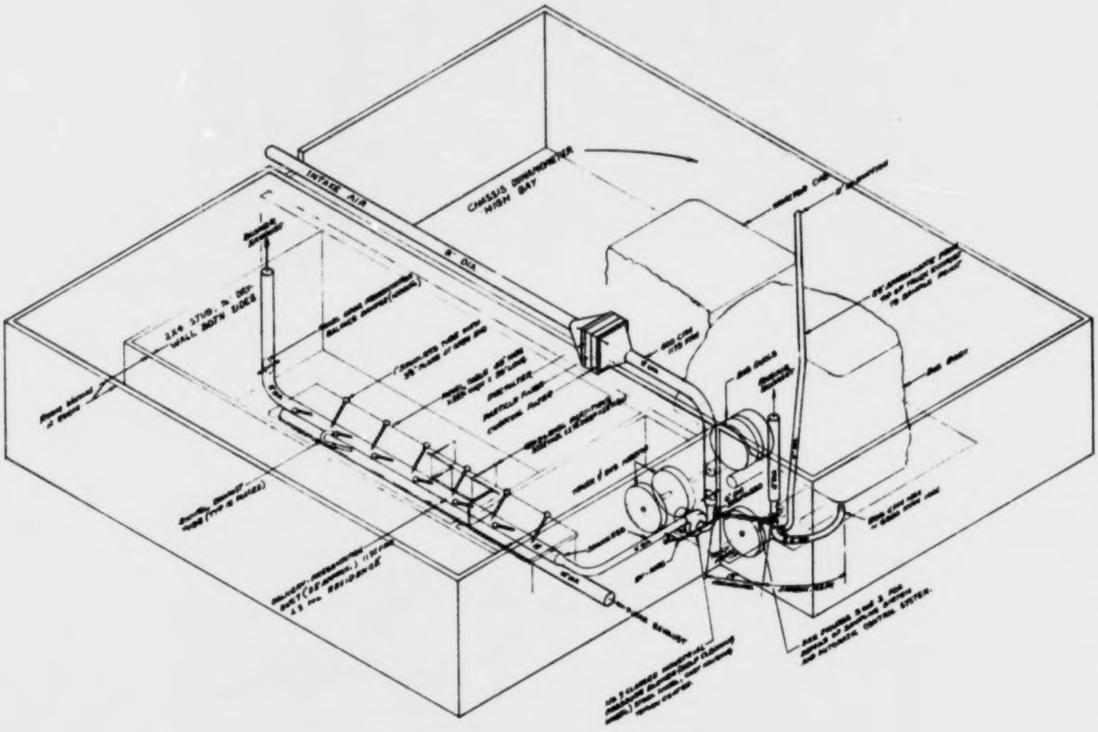


FIGURE 3. ISOMETRIC VIEW OF ODOR FACILITY

Figure 4 illustrates the odor panel and exposure facility for simultaneous evaluation of diluted samples of diesel exhaust. The odor panel, composed of ten housewives,

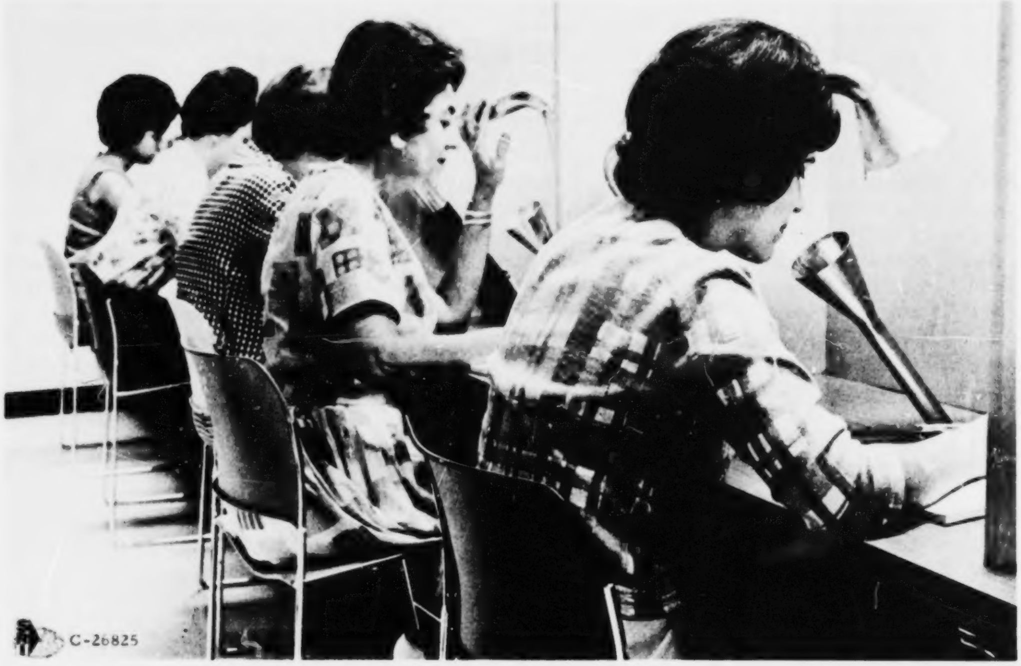


FIGURE 4. ODOR PANEL AND EXPOSURE FACILITY FOR SIMULTANEOUS EVALUATION OF DILUTED SAMPLE ODOR QUALITY/INTENSITY

evaluated the odor quality/intensity of the diluted sample using the Q/I kit. Note the 1-in. diameter, Type 304 stainless steel tube which protrudes from the table top in the center of each cubicle. A portion, 1 cfm, of the diluted exhaust sample passed through this tube and out through the 1- to 3-in. diameter diffuser cone. When the panelist exposed her nose and nose area to the gas sample issuing from the diffuser, she rotated up, away from the diffuser, a larger cone connected to a fume removal system.

To assure optimum panel performance, the major design criteria for the odor room were to maintain an environment as odor free as possible at a constant temperature and humidity, and operation of the vehicles on the road simulation equipment in the adjacent high bay area should not be apparent or recognizable to the panelists. These requirements dictated that a special odor panel "room within a room," shown in Figure 3, be designed and constructed for the Part I program. The inside dimensions of this facility are 15 ft wide by 24.5 ft long by 8 ft high with 367.5 sq ft of floor area and a 2940-cu ft volume. The interior appearance of this room is shown in Figure 4.

One cfm of the diluted sample was presented simultaneously to each of the ten panelists via stainless steel ducting/tubing. Provision was made to remove practically all of this dilute sample from the room by the individual fume exhaust devices during the times when the panel was not sniffing, or over 99 percent of the time. During those few seconds required to raise the fume removal device and sniff, the sample did escape into the room. To minimize the effect of this free odor on the room environment and panelist's background odor, a special 4-ton capacity air-conditioning, heating system was designed and installed. The system was capable of recirculating up to 1500 cfm of room air (one room air change every 2 min) through particulate and charcoal filters. Additionally, the environment control system could remove and replace in the room up to 800 cfm of particulate and charcoal-filtered makeup air. This permitted up to about 60 cfm to be removed at each of the twelve odor evaluation stations. Experience indicated that satisfactory operation could be achieved by recirculating 1400 cfm and adding approximately 400 cfm of makeup air. The fume removal system removed approximately 30 cfm at each of the twelve stations.

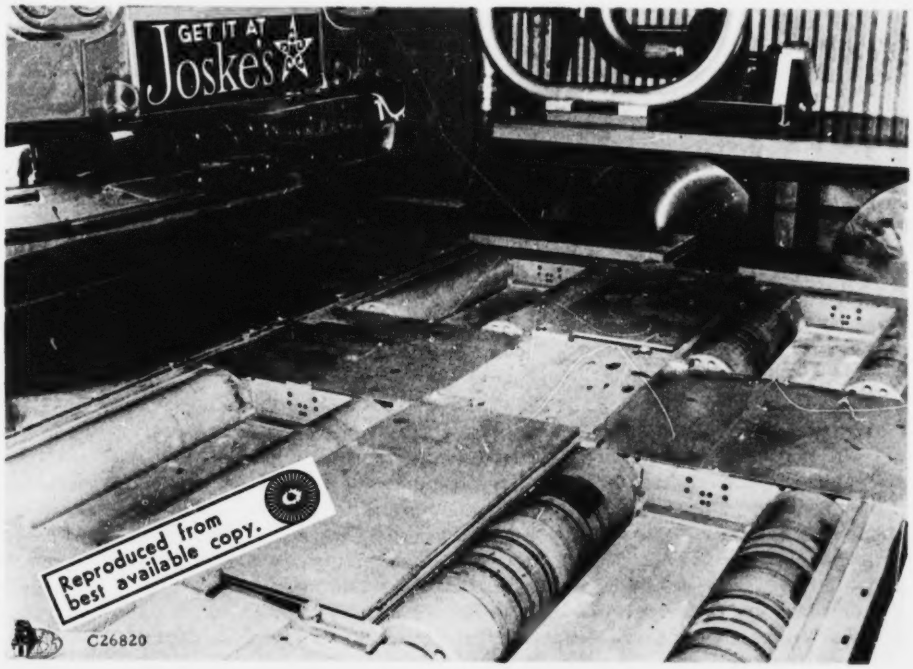
A positive room pressure of 0.01 in. of water was maintained. The odor room temperature was maintained at 75°F ± 2°F, and the room relative humidity at 45 ± 3 percent.

c. Laboratory Road Simulation Facility

The nature of the odor and smoke measurement techniques necessitated the design and construction of a special road simulation facility. A modified Clayton chassis dynamometer (Model CTFF 200 X 200), capable of handling tandem axle drive truck-tractors and absorbing up to 200 hp from each axle, was employed. Figure 3 provides an overall view depicting the locations of the road simulation equipment relative to the odor facility--sampling, dilution, and odor room, etc. In addition to simulating on the chassis dynamometer road load and constant power conditions, it was desired to simulate vehicle acceleration under loaded and open-rack engine operation. To do so, large solid disc flywheels were directly connected to the absorber roll of the chassis dynamometer. Three wheels were used, two capable of simulating 16,000 lb of vehicle weight each and the third capable of simulating 8430 lb. These wheels were arranged to permit up to 24,430-lb vehicle weight inertia simulation from a single-drive axle bus and 32,000-lb vehicle inertia from tandem drive vehicles such as intercity trucks (16,000-lb vehicle weight simulation per axle). Figures 5 and 6 illustrate the SwRI tandem axle chassis dynamometer and vehicle inertia simulation facility. Figures 7 and 8 illustrate the installation of the PHS full-flow smokemeter on a municipal bus and a typical intercity cab-over truck-tractor. Note in Figure 7 that the 3-in. horizontal exhaust pipe is extended for mounting the smokemeter optical unit. The optical unit is mounted on the typical 4-in. truck exhaust stack as shown in Figure 8. The same tractor, prepared for odor evaluations, is shown in operation in Figure 9.

2. Part II Facility Improvements

Although the basic odor, smoke, and exhaust emissions facilities established during Part I were utilized without change, minor improvements and refinements were made during the



Reproduced from best available copy.

FIGURE 5. SPECIAL SwRI LABORATORY ROAD SIMULATION FACILITY

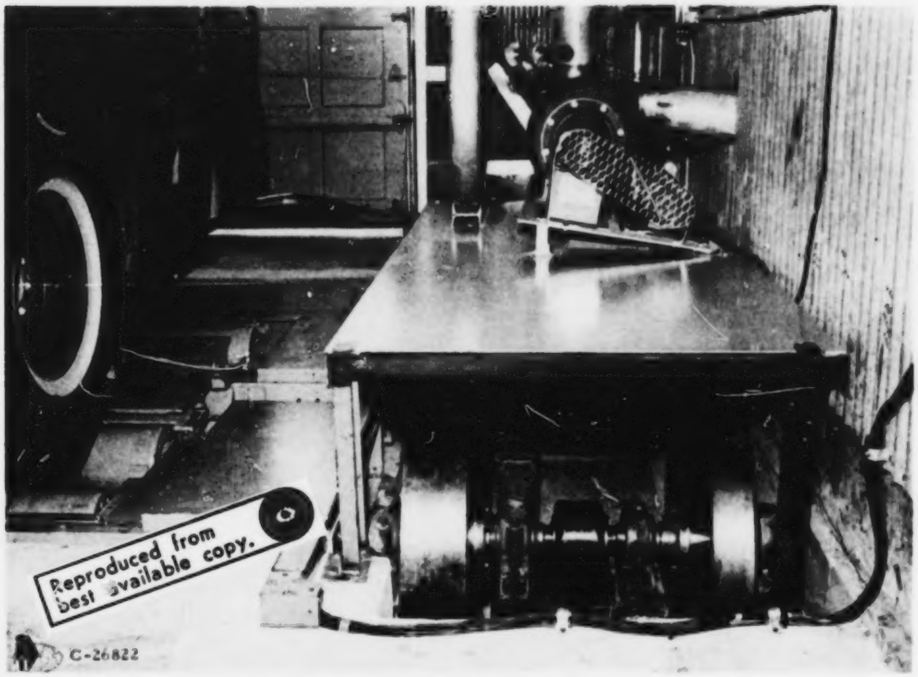

Reproduced from best available copy.
C-26822

FIGURE 6. SPECIAL SwRI CHASSIS DYNAMOMETER AND VEHICLE INERTIA SIMULATION EQUIPMENT

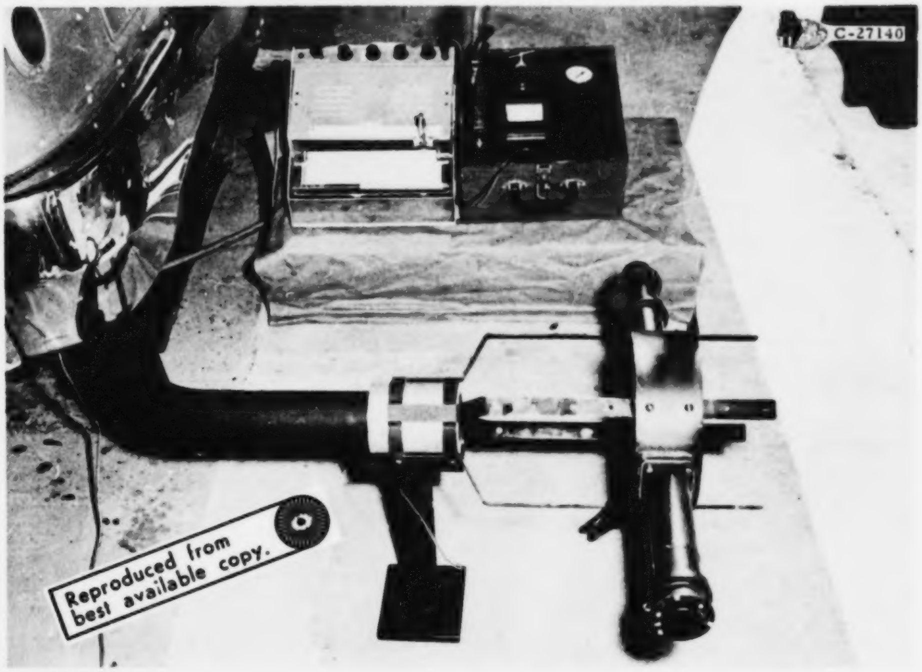

C-27140
Reproduced from best available copy.

FIGURE 7. U.S. PUBLIC HEALTH SERVICE SMOKEMETER MOUNTED ON EXTENDED GM MUNICIPAL BUS EXHAUST PIPE

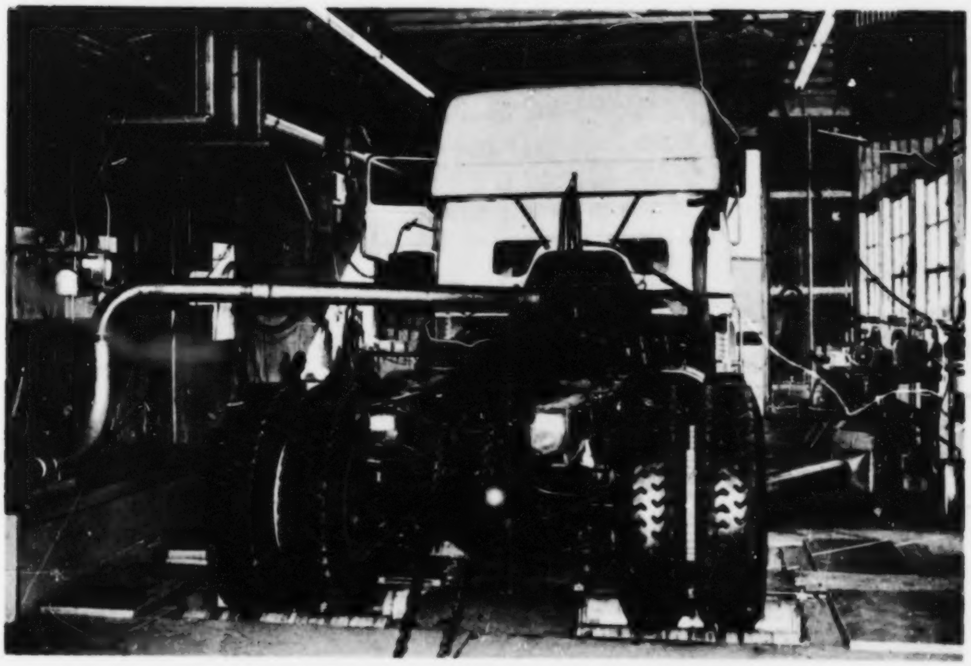
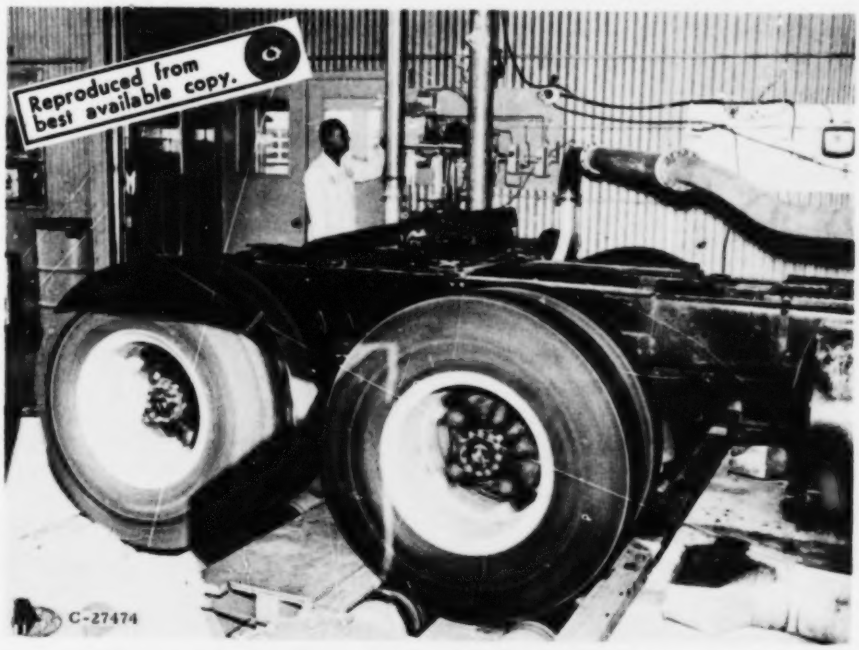


FIGURE 8. TRUCK-TRACTOR PREPARED FOR SMOKE EVALUATIONS WITH U.S. PUBLIC HEALTH SERVICE SMOKEMETER MOUNTED



Reproduced from best available copy.

FIGURE 9. TANDEM DRIVE AXLE TRUCK-TRACTOR UNDER ODOR EVALUATION

initiation of Part II. One improvement consisted of controlling the humidity of odor sample diluent air to eliminate a possible variable in the measurement of odor by the human panel. A design level for the diluent air presented to the nose and nose area of each panelist was 50-percent relative humidity at 75°F dry bulb. This condition results in an absolute humidity of 64 grains/lb of dry air at an air saturation temperature of 55°F.

To properly and simply maintain a constant absolute humidity, the air was passed through a spray chamber in which humidification or dehumidification occurred. With sufficient residence time and spray atomization, the exit air was saturated within 2 deg of the spray water temperature. The humidity system was placed after a Mine Safety Appliances particulate filter but before the existing Barnebey Chaney activated carbon odor filter. The majority of reheat occurred after the charcoal filter in order to obtain improved odor filtration efficiency possible with cooler air. To condition the 356 cfm of diluent air to a constant 64, plus or minus 5 grains of absolute humidity under both winter and summer conditions, required 3 tons of air conditioning. Installation and check-out of the diluent air humidity control system was successfully completed in March 1967 and has since proved to be maintenance-free and reliable.

Other improvements and refinements were also accomplished including replacement of the odor room humidifier with an increased capacity unit to more adequately maintain the odor room air relative humidity at 45 ± 3 percent. Control of the odor room relative humidity is an important factor in sensory evaluations of this type as the human olfactory system and consequent odor perception is sensitive to moisture content of the environment. The additional humidification was found necessary during odor room operation on cold dry winter days. Additional minor refinements were made to the odor measurement facility. Based on the typical exhaust sample temperatures measured during the procedural development portion of the Part I program, the span of the Foxboro analog pneumatic temperature divider for sample temperature compensation was changed from 200° -800°F to 100° - 450°F. This change was made to permit improved sample flow temperature compensation.

A remote switch to actuate an air solenoid valve was added to the automatic dilution system to permit operation of the exhaust sampling-dilution system by the vehicle operator. A fail-safe microswitch and signal light were added to indicate to the vehicle operator that the sample was being obtained. With this change, the operator had complete control of the vehicle dynamometer operation and the sample exhaust dilution system, as well as control of the human panel by the ready light and bell signal.

In addition to the 300-hp dynamometer stationary test bed facility provided for the Cummins NH-220, six-cylinder, 220-hp, four-cycle diesel engine, a complete engine-dynamometer test stand was provided to supply a continuous and constant source of characteristic two-cycle diesel exhaust. An available GM, Detroit Diesel Engine Division, 1-71 single-cylinder engine (similar to the multicylinder 71 series engines widely used in municipal and intercity buses and intercity truck-tractors) coupled to a 50-hp eddy current dynamometer was located adjacent to the analytical area and the central laboratory exhaust stack. The location of this small engine near the point of exhaust sampling for the odor room was mandatory to permit sampling, dilution and presentation of exhaust to the odor panel. This location made available exhaust samples for wet chemical and gas chromatographic analyses with no difficulty. For additional details regarding the single-cylinder, two-cycle engine facility and its unique capabilities, please see Section VIII, Chemistry Studies.

B. Equipment and Instruments

The Part II program utilized a number of items of equipment and instrumentation not involved in Part I. In an attempt to improve the drift and other minor difficulties experienced using a 6-volt, DC wet cell power supply for the PHS smokemeter, a Sola constant DC power supply was obtained to supply regulated 6-volt, 10-amp, DC power. A Beckman 315 infrared, equipped with a 5.25-in. sample cell, 5-in. filter cell, and a 10.5-in. reference cell plus 0.25-in. filter cap was procured to measure carbon monoxide in diesel exhaust in the range of 0 to 2000 ppm. An available 0 to 15-percent CO_2 Beckman 315 infrared was employed to measure CO_2 concentrations in the raw diesel exhaust, and a polarographic oxygen analyzer was also used. A large, 0- to 50,000-volt, 0- to 100-ma, full-wave rectified DC power supply, plus the necessary volt and ampmeters, etc., was provided for evaluation of electrostatic precipitator exhaust gas device.

The Institute Control Data Corporation, CDC 160A, and CDC 3600 digital computers were employed during the statistical analysis of the odor, smoke, and emissions data.

For the chemistry services, a Varian Aerograph 600D gas liquid chromatograph (GLC) with hydrogen flame ionization detector was utilized during the odor correlation investigations. This GLC was equipped with a flow splitter located between the column and detector for simultaneous sample analysis and odor evaluation. An L&N Speedomax W recorder with disc integrator and the other necessary accessories, precolumns, columns, traps, and hydrogen generator were also provided. Many of the wet collected samples of diesel exhaust for chemical analysis involved a color change. A Bausch & Lomb Spectronic 20 colorimeter was used to measure color change.

C. Description of Fuels

This subsection covers the description of the number 1 and number 2 commercial type diesel fuels utilized during this program as well as typical specifications of fuels purchased by the San Antonio Transit System for municipal buses and the Ryder Truck System for intercity trucks. Listed on Table 1 are typical specifications of a number 1 kerosene type fuel commonly utilized in municipal buses and of a number 2 diesel fuel normally burned in intercity truck-tractor rigs. To eliminate the possible effect of diesel fuel type and composition on the odor, smoke, and other diesel exhaust emissions measurements, only known commercial number 1 and number 2 diesel fuels, stored in separate 1000-gal tanks, were consumed.

TABLE 1. COMMERCIAL DIESEL FUEL SPECIFICATIONS--TYPICAL

Commercial Designation		1	2
Application		City Bus	Intercity Truck
Specification Provided by		S.A. Transit System	Ryder Leasing
Property	ASTM Test Method No.	Typical Specifications	
Cetane	D613	46	52
Pour Point, °F	D97	-60	-10
Flash Point, °F	D93	133	182
Gravity, °API			36.7
Viscosity, SUS at 100°F	D445 D446	32	35.5
Carbon Residue (10% Res), %	D189	0.07	0.03
Total Sulfur, %	D129	0.04	0.08
Alkali or Mineral Acids	D663 or D664	0.03	
Water and Sediment	D96	0	
Distillation Range	D86		
Initial Boiling Point, °F		350	392
10% Point, °F			444
50% Point, °F			516
90% Point, °F		465	574
End Point, °F		518	610

For the initial few months of the Part II program, the test fuels remaining from the Part I program were used. These fuels are described in Table 2 which lists pertinent inspection results such as distillation range, cetane number, sulfur content, aromatic, olefin and saturates composition. The number 1 diesel fuel was identified as SwRI code EM-3-F and the number 2 material as EM-10-F. The inspection data for samples of these reference supplies indicate the distillation range to be slightly lower overall than the typical specifications of Table 1. The cetane number or ignition quality of both fuels was about 2 cetane numbers lower than the typical specification of 46 and 52 for numbers 1 and 2 fuel. The greatest difference appeared to be the total sulfur content which was higher than the specification of Table 1. The sulfur values of the fuels used for reference, however, were not considered excessive.

TABLE 2. INSPECTION OF COMMERCIAL NUMBER 1 AND NUMBER 2 DIESEL FUELS USED IN PART II PROGRAM

Commercial Fuel Type	1		2	
Sample Information Code Date Analyzed	EM-3-F(1) 1/27/67	EM-3A-F(2) 11/28/67	EM-10-F(3) 1/27/67	EM-29-F(4) 11/28/67
Property				
Distillation Range				
Initial Boiling Point, °F	326	340	320	352
10% Point, °F	360	360	398	414
20% Point, °F	372	372	424	441
30% Point, °F	380	380	456	460
40% Point, °F	388	389	472	476
50% Point, °F	396	398	488	491
60% Point, °F	404	405	504	504
70% Point, °F	414	415	518	519
80% Point, °F	428	429	536	537
90% Point, °F	450	449	557	562
End Point, °F	489	521	578	606
% Recovery	98.0	99.0	97.5	98.5
% Residue	1.8	1.0	2.2	1.3
% Dist. Loss	0.2	0.0	0.3	0.2
Cetane Number	43.7	45.0	49.5	50
F.I.A. Analysis				
Aromatics, %	15.2	15.9	19.5	25.0
Olefins, %	2.5	0.0	2.9	0.0
Saturates, %	82.3	84.1	77.6	75.0
Total Sulfur	0.09	0.08	0.11	0.07
Gravity, °API at 60°F		44.8		36.9

(1) Initial 1000-gal supply utilized until August 22, 1967.

(2) New 1000-gal supply utilized after August 22, 1967.

(3) Initial 1000-gal supply utilized until June 7, 1967.

(4) New 1000-gal supply utilized after June 7, 1967.

On August 22, 1967 and June 7, 1967, additional 1000-gal supplies of number 1 and number 2 diesel fuel were obtained. These fuels were coded EM-3A-F (number 1 fuel) and EM-29-F (number 2 fuel). As with the originally obtained fuel supplies, these fuels were purchased under the typical specifications listed in Table 1. The inspection reports are also listed on Table 2. The number 1 material, coded EM-3A-F, inspection revealed the boiling range of 340° to 571°F to be nearer the typical number 1 fuel specification of 350° to 518°F shown in Table 1 than the original reference fuel supply EM-3-F. The sulfur content of 0.08 percent was essentially the same as the EM-3-F and higher than the typical specification. The cetane number was slightly less than typical but somewhat greater than the cetane rating of EM-3-F. The F.I.A. analysis revealed the composition of EM-3A-F to be similar to EM-3-F in terms of percent aromatics, olefins, and saturates. Considering the number 2 diesel fuel Code EM-29-F relative to the original EM-10-F, the boiling range of 352° to 606°F was higher than the EM-10-F range of 320° to 578°F but more in line with the specifications of 392° to 610°F listed on Table 1. Likewise, the sulfur content was lower, 0.07 percent versus 0.11 percent (EM-10-F). The fuel cetane rating was essentially the same as EM-10-F (50 versus 49.5) compared to the specified typical number of 52. F.I.A. analysis of composition indicated an increase in aromatic content with a decrease in olefins to 0 percent and slight decrease in saturates. Overall, the comparison of the new reference fuels EM-3A-F and EM-29-F with the original reference fuels EM-3-F and EM-10-F indicates that there are no gross differences apparent, and, where differences were noted, they generally represented better conformity with the typical specifications.

III. STUDY OF ENGINE DERATING ON ODOR AND SMOKE

The objective of this study was to determine the effect of engine power derating as a means for reducing diesel powered vehicle odor and smoke. Derating means reducing the available power from a given size or displacement engine and is usually accomplished by decreasing the amount of fuel injected into the engine combustion chamber. Previous studies of the effect of load on diesel exhaust odor, conducted during the Part I program, indicated that the power output of the engine had only a secondary influence on the quality and intensity of the exhaust odor. Since engine derating is a means of reducing the maximum power output, it was felt that these experiments would have greater effect on the visible exhaust smoke discharge than on the odor intensity and quality. Therefore, the approach adopted was to measure odor at the highest and lowest power levels investigated and to measure smoke output at these endpoints, as well as intermediate power settings.

During the March 17, 1967, meeting with the Project Officer, Mr. George Kittredge, Mr. Andrew Rose, Mr. Ralph Stahman, Mr. Don Hill, and Mr. Howe Hopkins, at the National Center for Air Pollution Control in Cincinnati, Ohio, it was agreed to consider three types of widely used engines employed in intercity type truck-tractors. The engines selected for this experimental investigation were as follows:

(1) Detroit Diesel Division in-line 6-71 N type (2-cycle) engine;

(2) Cummins NH-220, naturally aspirated (4-cycle) engine; and

(3) Mack END-673P, naturally aspirated (4-cycle) engine.

Requests were then made of the Detroit Diesel Division, the Cummins Engine Company, and Mack Trucks Incorporated for their recommended method of engine derating. According to the Detroit Diesel Division representatives, Mr. Stan Ford and Mr. David Merrion, who visited the Vehicle Emissions Research Laboratory on March 8 and 9, 1967, derating of the Detroit Diesel, two-cycle, 71 series engine would be by means of injector change. This involves replacement of each unit injector plunger and barrel assembly with smaller size components. To accomplish engine derating, Detroit Diesel offered to supply the necessary sets of new, flow-balanced, and calibrated unit injectors. According to Mr. Al Carey, Cummins Engine Company, the recommended technique for derating the NH-220 engine was to recalibrate the PTG injection pump. This calibration procedure would effectively derate the engine power and torque output over the entire engine speed range and would be satisfactory to as low as 180 hp at 2100 rpm. The approach was to successively remove and take the injection pump to the local Cummins Distributor for recalibration and flow test. Correspondence from Mr. W. J. Pelizzoni of Mack Trucks included drawings and recommended procedures for resetting the cam angle and cam plate adjustments with the American Bosch APE 6BB type fuel injection pump for engine derating purposes.

The results of the engine derating investigations are presented in the order of test; Detroit Diesel, Cummins, and Mack. Complete data regarding the odor and smoke measurements obtained for each make of engine may be found in Appendix A to this report.

A. GM Detroit Diesel Division 6-71 N Engine Results

A series of engine derating experiments was conducted using a tandem axle cab-over General Motors Corp. truck-tractor powered by a Detroit Diesel in-line 6-71 N type engine. A description of the engine and vehicle may be found in Table 1 of Appendix A. According to this list of specifications, the truck-tractor employed a Fuller RT9-10 "Road-Ranger" ten-speed transmission and single-speed tandem drive Eaton rear axles. In addition to engine, vehicle, and driveline specifications, pertinent engine maintenance data including total mileage, miles since injector change, and the mileage since major overhaul are given.

The odor evaluation conditions employed during this engine derating study, shown in Table 2 of Appendix A, are essentially the same as those developed during the Part I program (Ref. 1), for the evaluation of vehicle exhaust odor from truck-tractors. Since the driveline, transmission, and rear axle for the GMC tractor were essentially the same as utilized during Part I, no changes were made to the Part I procedures repeated in Tables 3 through 7 of Appendix A. The two constant speed odor evaluation conditions are described in Table 3 for the 1700- and 2100-rpm engine speed operation. The other constant speed condition, the idle after powered operation, is described in Table 4. The idle-acceleration evaluation procedure, in which the vehicle undergoes acceleration in first gear after a 60-sec idle, is described in Table 5. The prolonged high speed acceleration from 8th into 9th gear procedure is described in Table 6. The closed-rack deceleration after a constant speed operating condition, is detailed in Table 7.

Initial plans were to conduct a series of experiments with three sets of new, flow-balanced and calibrated unit injectors furnished by Detroit Diesel. The injector model, type, and nominal flow were: (1) 71N50 type N50 at 52 ml/stroke, (2) 71N55 type N55 at 55 ml/stroke, and (3) 71N60 type N60 at 59 ml/stroke.

The results of this series of three tests were inconclusive in that the expected power improvement and smoke did not change with injector size and fuel delivery rate as expected.

As soon as these difficulties were found to exist, both the Project Officer, Mr. George Kittredge, and the cognizant technical representative of Detroit Diesel, Mr. David Merrion, were informed. The smoke levels produced under operating conditions of maximum power measured at 1000, 1100, 1300, 1500, 1700, 1900, 2100, and 2200 rpm showed little measurable difference in vehicle power or smoke as measured by the PHS smokemeter. The vehicle produced approximately 140 to 150 hp at the rear wheels at 2100-rpm engine speed. The smoke levels measured under these conditions were substantially less than 10-percent absorbance.

In discussions with Mr. Merrion, it was learned that the normal flow rate to which each set of injectors was calibrated within a ml per stroke, plus or minus, actually were only 7 ml in flow rate different between the N50 and N60 injector type. At 2100-rpm engine speed, the N60 injectors should produce approximately 159 brake hp at the rear axle, assuming an 82-percent transmission and driveline efficiency and approximately 20-hp difference between the N60 and N50 injectors should have been achieved. These experiments indicated that both the N60 and N50 injectors resulted in identical power levels of 140 wheel hp at 2100-rpm engine speed. As an independent check, a reconditioned set of N70 injectors, which are sometimes used in certain types of diesel truck-tractor operation, was installed in the engine. Soon after the initiation of this set of experiments, the keeper on one of the four exhaust valves in No. 5 cylinder sheared, causing the exhaust valve to be drawn into the cylinder, resulting in engine failure. According to the Hertz Rental Agency, who repaired the engine, the damage was rather slight in that the piston and head were not damaged or cracked; only a few valve seats were damaged in No. 5 cylinder, and the exhaust valve and connecting rod were bent.

Prior to termination of this experiment, smoke data were obtained at the low engine speed conditions which indicated that this tractor would smoke approximately five times as great with the N70s as with the N60 injectors. During continued discussions with Mr. Merrion, it was learned that the N65 injectors, which have a nominal output of 66 ml per stroke, are the largest injectors recommended for highway truck operation. This particular 6-71 engine was equipped with N65 injectors.

The initial set of experiments, with three types of flow-balanced new injectors, did not permit an adequate evaluation of the effect of derating for this particular truck engine. As a result, an additional set of flow-balanced injectors was obtained from the manufacturer and a final series of experiments conducted. Listed below is the schedule of tests of the calibrated unit injectors, furnished by Detroit Diesel, as well as the original injectors. The final series of evaluations was made during the period May 22 through 25, 1967. By changing the group of six unit injectors, the nominal flow in milliliters of fuel per stroke maximum could be varied through the range of 52 to 66 ml per stroke. Odor measurements were obtained at approximately 7-ml increments at 52 ml per stroke (71 N50), 59 ml per stroke (71 N60), and 66 ml per stroke (71 N65). Odor tests were made on a back-to-back basis in which the vehicle was operated one day with one set of injectors and on the following day with a different set of injectors. Because of the engine failure and the time lag between the initial and the final series of experiments, the 71 N50 and 71 N60 injectors were run back-to-back

Date	Injector Model	Condition	Nominal flow, ml/stroke
5/3/67	71 N50	New	52
5/3/67	71 N55	New	55
5/5/67	71 N60	New	59
5/8/67	71 N70	Rebuilt	-
5/22/67	71 N65	Original	-
5/23/67	71 N65	New	66
5/25/67	71 N60	New	59

on May 4 and 5, and the 71 N60 and 71 N65 injectors were run back-to-back on June 8 and 9, 1967. Smoke measurements were made for all sets of new injectors listed, as well as a set of rebuilt 71 N70 injectors (until engine failure) and with the engine equipped with 71 N65 injectors as received from the rental agency.

The results of the initial series of investigations, conducted with the 71 N50 and 71 N60 injectors, are compared in Table 8 of Appendix A. This initial series of evaluations indicated that fuel delivery rate had little if any noticeable effect on the resultant vehicle exhaust odor. This tends to confirm earlier investigations during Part I procedural development studies. More important, however, was that under truck operating conditions and evaluation procedures, this particular engine produced significantly low levels of diesel odor. These odor evaluations were particularly difficult and required increased concentration by the panelists due to their relatively low intensity. Considering the overall diesel composite ratings for operating conditions I and II, the 1700- and 2100-rpm constant speed conditions, the odor evaluation intensities were about 2.5, substantially lower than the 3.8 rating given during condition III, the idle, and the rating of 3.6 given for the deceleration condition IV. The constant speed ratings, conditions I and II, were essentially the same as conditions IV and V, the idle-acceleration and the high speed acceleration conditions, respectively. The highest levels of the burnt-smoky quality were found to occur during the idle-acceleration, condition III, and condition IV, the deceleration after high speed operation. These "B" burnt-smoky ratings of approximately 1.0 reflect the low intensity of the diluted (700:1) exhaust sample.

Summarized on Tables 9 and 10 of Appendix A are the vehicle odor evaluations for the 71 N50 and the 71 N60 injectors, respectively. The average odor panel responses are grouped by each of the six operating conditions on these tables. Listed in Tables 9A through 9E and 10A through 10E are supporting data which are summarized in Tables 9 and 10, respectively. These supporting tables are provided to indicate the panel distribution for each of the twenty-eight runs conducted for each derated engine experiment. Table 9A shows the distribution for the overall diesel composite standard, "D" rating. Table 9B contains the "B" burnt-smoky panel response, and Table 9C lists the "O" oily responses. Similarly, Tables 9D and 9E contain the odor panel judgments for the "A" aromatic-aldehydic and "P" pungent standards, respectively. Tables 10A through 10E are likewise organized.

Since the smoke and power results obtained with the initial series of tests with the 71 N50 and 71 N60 injectors seemed inconclusive (to be further discussed in later paragraphs), it was decided to conduct an additional series of odor evaluations with the 71 N60's and a new set of 71 N65 injectors operated back-to-back on successive days. This was felt necessary due to the fairly light odor evaluations obtained with the 71 N50's and 71 N60's previously discussed and because of the time delay of approximately 2 wk during which time a cylinder kit was installed in the No. 5 cylinder and the engine broken in. Because the engine cylinder head was removed and engine repair and maintenance performed between the initial and final series, a new back-to-back comparison was necessary. Listed in Table 11 of Appendix A is an overall comparison of the odor evaluations for the final series of investigations in which the 71 N60 and 71 N65 injectors were evaluated.

As in the initial series of derating experiments, the size of the injector and its nominal fuel delivery characteristics had little apparent effect on the resultant odor. In review of the data of Table 11, there did not seem to be any gross differences in odor except possibly during the idle, condition III, and the idle-acceleration, condition IV, in which the diesel composite ratings appeared to be greater with the larger 71 N65 than with the 71 N60 injectors. This difference in overall intensity did not appear to be reflected in the "B" burnt-smoky ratings. Similar to the initial series of investigations, the Table 11 data indicate that the cruise operation was lower in intensity per the overall diesel composite rating than the remaining conditions. The idle and deceleration appeared to have the highest rating of approximately "D"-4. The evaluation of the 71 N65 and 71 N60 injectors is summarized in Tables 12 and 13 of Appendix A. These two tables are organized similar to Tables 9 and 10. Grouped by operating condition, the average results for the diesel composite and the four quality standards are compared. These tables list the responses for the six operating conditions conducted in quadruplicate. Supporting tables which indicate the distribution of the panel response are contained in Tables 12A through 12E and 13A through 13E for the 71 N65 and 71 N60 injector experiments, respectively. These tables are organized similar to the previously discussed supporting Tables 9A through 9E.

In summary, derating the engines by changing injector size, fuel delivery and resulting power had little, if any, noticeable effect on vehicle exhaust odor and tends to confirm the effect noticed during Part I. This series of odor evaluations was the first made with a two-cycle powered truck-tractor using the PHS-SwRI odor measurement method, and some special comments may be offered in this regard. First, the particular Detroit Diesel 6-71 N, two-cycle, four-valve diesel engine evaluated produced low levels of diesel odor. This was substantiated by the repeated operation and measurement by the ten-person odor panel under realistic truck operating conditions at 700:1 dilution ratio. The reason for the fairly low odor intensity as compared to a two-cycle powered municipal bus is not known but may be attributed in part to the different type combustion system, the generally higher speed operation of 1700 to 2100 rpm, the four exhaust valves per cylinder, the N type engine configuration, and its increased compression ratio relative to the two-valve E series bus engines evaluated. An additional major factor was the 700:1 dilution ratio established as reasonable truck exhaust dilution during the Part I atmospheric field survey studies.

In addition to the odor evaluation of the Detroit Diesel powered truck-tractor, smoke inspections were obtained with the previously listed sets of unit injectors. The smoke evaluation conditions used during the derating study are listed on Table 14 of Appendix A. The smoke measurement method, inertia simulation, and operating conditions employed were essentially the same as those developed and used during the Part I program. To obtain as complete smoke inspection data as possible, several additional constant speeds were included such that smoke was measured at 1000-, 1100-, 1300-, 1500-, 1700-, 1900-, 2100-, and 2200-rpm engine speeds under open-rack, maximum power operation. With the transmission in 8th gear, the vehicle speeds varied from 18 to 38 mph with an engine speed of 1000 to 2200 rpm. Table 16 describes the smoke evaluation procedure used during transient acceleration vehicle operation.

Included as Table 17, Appendix A, and as Table 3 of the text is an overall summary of the effect of derating the Detroit Diesel powered truck-tractor on exhaust smoke. This table summarizes all of the smoke inspection measurements made. The data are presented chronologically such that the initial experiments conducted on May 3, 5, and 8 may be analyzed separately from the final experiments conducted on May 22, 23, and 25, 1967. During the smoke inspections, vehicle wheel power output and the smoke intensity measurements were made in triplicate. Listed in Table 3 are the average horsepower and smokemeter readings in percent light absorbance for each of the eight constant speed conditions ranging from 1000 rpm up to 2200 rpm for each set of injectors. Considering the initial three sets of new injectors evaluated on May 3 and 5, the effect of injector size on vehicle power output and smoke was almost negligible. Because of the almost nil effect of the 71 N60 injectors relative to the 71 N50 injectors on vehicle horsepower and smoke under both constant speed and accelerating conditions, a set of rebuilt 71 N70 injectors was installed. The 71 N70 injectors are not normally used in intercity truck application and are used only in selected special vehicles; the 71 N65 are the largest routinely recommended by the manufacturer for use in the truck-tractor application. The 71 N70 injectors, though evaluated at only 1000 and 1100 rpm, resulted in approximately five to six times the smoke levels recorded with the new flow-balanced, manufacturer-supplied, 71 N60 injectors. As a result of this brief experiment, terminated due to engine failure, it was determined that it was possible to make this engine smoke if sufficient fuel delivery could be obtained.

During the time required for the engine to be rebuilt, a set of flow-balanced calibrated 71 N65 unit injectors was obtained from the manufacturer. These larger injectors, having a nominal

TABLE 3. OVERALL SUMMARY OF THE EFFECT OF DERATING A DETROIT DIESEL 6-71 N POWERED TRUCK-TRACTOR ON EXHAUST SMOKE

Vehicle: GMC Tractor 45407.
Engine: Detroit Diesel 6-71 N.

Operating Conditions: See Table 14.
Fuel: EM-10-F (No. 2 Diesel).

Constant Speed (all open-rack, maximum power output)

Date:		5/3/67		5/3/67		5/5/67		5/8/67		5/22/67		5/23/67		5/25/67	
		New 71 N50		New 71 N55		New 71 N60		Rebuilt 71 N70		Original 71 N65		New 71 N65		New 71 N60	
Operating Condition	Engine Speed, rpm	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %
A	1000	85	6.5	90	6.7	90	9.5	90	51.0	90	25.7	90	8.5	90	5.7
B	1100	90	6.3	100	5.3	95	8.2	95	47.0	100	18.5	100	6.5	100	4.7
C	1300	100	4.3	110	3.5	100	3.5	Engine Trouble*		120	10.5	110	4.0	110	3.2
D	1500	120	2.8	120	2.5	115	2.1	"	"	140	8.5	130	3.5	120	2.5
E	1700	125	2.7	130	2.5	120	2.0	"	"	150	7.2	140	3.5	130	2.5
F	1900	130	2.7	140	2.5	130	1.5	"	"	160	8.5	150	3.2	140	2.7
G	2100	140	2.8	150	2.2	140	1.5	"	"	170	11.2	160	2.6	140	2.5
H	2200	130	2.5	100	1.5	110	1.2	"	"	160	3.5	120	2.3	90	2.3

Acceleration (40 hp at 30 mph preset and retained)

Operating Condition	Transmission Gear No.	New 71 N50 Smoke, %	New 71 N55 Smoke, %	New 71 N60 Smoke, %	Rebuilt 71 N70 Smoke, %	Original 71 N65 Smoke, %	New 71 N65 Smoke, %	New 71 N60 Smoke, %
I	5th	2.2	1.0	2.0	Engine Trouble	9.5	1.6	2.6
I	6th	2.7	1.2	2.0	" "	10.0	2.0	3.0
I	7th	2.2	1.5	1.8	" "	10.6	2.0	2.6
I	8th	1.8	1.7	1.8	" "	11.3	2.0	2.6
I	9th	2.0	2.0	1.7	" "	7.7	2.2	2.5
I	10th	2.0	1.7	2.2	" "	7.0	2.2	2.0

---

*Exhaust valve keeper, No. 5 cylinder, failed and valve drawn into No. 5 cylinder. Repairs to engine involved new No. 5 connecting rod and all new valve seats. Piston, head, and injector not damaged. Remainder of engine left intact.

delivery of 66 ml per stroke (7 ml per stroke more than the 71 N60 injectors) were evaluated in the rebuilt 6-71 N engine on May 23, 1967. These results may be compared with the original engine injectors which were rebuilt approximately 16,000 miles prior to test and were evaluated on May 22. Comparing the original engine equipped 71 N65 with the new 71 N65 equipped engine on Table 3, the smoke levels were greater for the engine with the original injectors than with the new units. Although the smoke was approximately two to three times greater with the original units than with the new units, the power was essentially 10 hp more with the original units than with the flow-balanced, calibrated 71 N65 injectors. Approximately four to five times greater smoke was observed during the accelerating conditions with the original 71 N65 as with the new 71 N65 units. The next comparisons of interest are the results obtained on May 25 with the new 71 N60 relative to the new 71 N65 injectors previously discussed. In most cases, the 71 N60 unit injectors produced approximately 10 hp less and slightly less smoke. The May 25 data for the 71 N60's had substantially lower smoke than that recorded on May 25 before the engine was damaged. The horsepower levels before and after the engine repair were approximately the same.

Listed in Tables 18 through 23 of Appendix A are the individual smoke evaluation summaries for the engine equipped with each of the various sets of unit injectors. Each of these tables is organized to present the maximum, minimum, and average PHS smoke readings in percent absorbance for each of the eight constant speed operating conditions as well as the acceleration in 5th through 10th gears. Also listed are the horsepower output and vehicle speed. Table 18 lists the results for the 6-71 N engine equipped with the new 71 N50 unit injectors. Tables 19, 20, 21, 22, and 23 contain the results of the smoke inspections with the 6-71 N engine equipped with new 71 N55, new 71 N60, original 71 N65, new 71 N65, and the rerun of the new 71 N60 unit injectors.

B. Cummins NH-220 Engine Results

Derating experiments with a Cummins NH-220 powered, tandem drive tractor were conducted to determine the effect of engine power rating on exhaust odor and smoke. For these investigations, the basic plan was to evaluate the smoke and odor emissions from the tractor with the engine pump adjusted to produce 220 hp at 2100 rpm (the basic engine hp setting), 200 hp at 2100 rpm, and 185 hp at 2100 rpm. To do this, the Cummins Engine Company recommendation of adjusting a type PTG injection pump for power and torque by the local Cummins distributor was followed. This engine derating technique involved removal of the engine injection pump and adjustment and flow calibration to the Cummins engine specifications of both torque and horsepower using the recommended factory calibration technique. This method was effective in changing both the torque and power curves. Listed below are the various derating experiments conducted using the Ford cab-over truck-tractor described in Table 1 of Appendix A.

Date	Injection Pump Calibrated at 2100 rpm for	Injection Pump Condition
5/31/67	220 hp	As received
6/1/67	200 hp	Cummins calibrated
6/2/67	220 hp	Cummins calibrated
6/6/67	185 hp	Cummins calibrated

The results of engine derating on the Cummins NH-220 powered truck-tractor emissions are contained in Tables 24 through 33 of Appendix A. Since the only major difference between this and the Detroit Diesel truck was the engine, identical odor measurement conditions and procedures could be employed. Odor evaluations were conducted at the maximum and minimum power ratings investigated. The results of the odor evaluations with the engine set for 220 and 185 hp are compared on Table 24 of Appendix A. The comparison was made on the basis of overall numerical average of the four-run judgments by the ten-person odor panel under each of the six operating conditions. The lowest overall average "D" composite ratings were given during the constant speed operation in 7th gear at 1700 and 2100 rpm. These ratings of 2.4 and 2.0 average were somewhat lower than the highest "D" ratings made during the idle and the deceleration (averaged approximately 4.6 and 5.6, respectively). The "B" burnt, "O" oily, "A" aromatic, and "P" pungent quality ratings followed somewhat the same trend. The effect of engine power level had little noticeable effect on exhaust odor quality and intensity for the particular vehicle and engine configuration tested.

Summarized on Tables 25 and 26 of Appendix A are the average panel responses with the engine rated at 220 and 185 hp at 2100 rpm. Each of these summary tables is supported by five tables of data which illustrate the panel response distribution for each of the twenty-eight runs conducted in random order, twenty-four runs with exhaust sample and four runs without exhaust (blank). The "D" diesel and "B," "O," "A," and "P" quality standard results are shown on Tables 25A through 25E for the engine adjusted to 220 hp and on Tables 26A through 26E for the engine adjusted to 185 hp.

To summarize, derating had little, if any, noticeable effect on the exhaust odor quality and intensity. This effect, noted with the one truck and engine system, tends to confirm the previously reported trend discovered during the Part I studies. Comparing the results of the single truck against the ten-truck variability results reported in the March 1967 final report, the "D," "B," "O," "A," and "P" responses were not greatly different from those previously obtained. In some cases, for instance, the "D" composite under cruise was slightly lower than the overall average during the ten-truck variability study. Although the single truck results were slightly higher than the overall ten-truck average for conditions III, IV, and VI, the single truck appears to fall within the scatter of data obtained during the ten-truck variability study.

Measurements were made of the resulting smoke intensities using the PHS smokemeter with the vehicle in the as-received nominal 220 hp at 2100-rpm engine rating, and with calibrated injection pumps adjusted for 200, 220, and 185 hp. The smoke evaluation conditions employed were identical to those developed during Part I listed on Table 27 of Appendix A. In addition to the normally operated 1700-, 1900-, and 2100-rpm engine constant speed, two additional constant speed conditions, 1500- and 2200-rpm, were included. The evaluation procedures employed during the five constant speed conditions are described in Table 28 of Appendix A. The procedure used during acceleration was identical to that described in Table 16 of Appendix A and employed during the two-cycle engine derating experiments.

Shown on Table 29 and repeated in the text as Table 4 is the overall summary of the effect of derating a NH-220 powered truck on smoke. Constant speed conditions are listed followed by the

TABLE 4. OVERALL SUMMARY OF THE EFFECT OF DERATING A CUMMINS NH-220 POWERED TRUCK-TRACTOR ON EXHAUST SMOKE

Vehicle: Ford Tractor 55961.
Engine: Cummins NH-220.

Operating Conditions: See Table 27.
Fuel: EM-10-F (No. 2 Diesel).

Date:

Constant Speed (all open-rack, maximum power output)

Operating Condition	Engine Speed, rpm	Injection Pump Calibrated at 2100 rpm for							
		As Received		200 hp		220 hp		185 hp	
		Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %
A	1500	140	18.7	120	7.7	140	21.0	120	4.7
B	1700	150	17.7	140	10.7	150	20.7	130	7.7
C	1900	160	18.0	140	13.0	160	20.0	140	10.3
D	2100	160	17.0	150	15.0	160	20.0	140	13.7
E	2200	140	12.6	140	13.0	160	16.7	130	10.3

Acceleration (40 hp at 30 mph preset and retained)

Operating Condition	Transmission Gear No.	As Received Smoke, %	200 hp Smoke, %	220 hp Smoke, %	185 hp Smoke, %
F	5th	10.5	8.3	14.0	11.3
F	6th	15.0	10.0	15.0	9.3
F	7th	16.3	11.3	16.7	9.7
F	8th	16.7	11.7	17.3	10.7
F	9th	16.0	10.7	18.0	7.7
F	10th	13.3	8.3	19.7	4.7

acceleration from 5th into 6th into 7th into 8th into 9th and into 10th gear with 40 hp at 30 mph preset in the water brake dynamometer and retained during the acceleration. On May 31, 1967, the tractor was operated in the as-received engine condition with pump set at a nominal 220 hp at 2100 rpm. On June 1, the vehicle was operated with the pump adjusted to 200 hp at 2100 rpm. The pump was then adjusted to 220 hp and the resultant smoke and power measured on June 2, followed by the 185-hp setting on June 6, 1967.

Comparing the power levels measured for the three settings, the vehicle power tended to increase about 10 hp from 185 to 200 hp and an additional 10 hp from 200- to 220-hp pump setting. For example, at 1700-rpm engine speed, the vehicle power increased from 130 to 140 hp for the pump adjusted at 185 hp versus the pump adjusted to 200 hp. The wheel power increased an additional 10 hp when the pump was adjusted to produce 220 engine hp. The effect of engine derating on smoke output between the 185- and the 200-hp pump setting was slight, but the difference in smoke between the 200- and 220-hp pump setting was substantial. As an example, the 1700-rpm smoke levels changed from 7.7-percent at 185 hp to 10.7 percent at 200 hp to 20.7 percent at 220 hp. This same type of trend was noticed for practically all other conditions operated.

Comparing the data of Table 4 for the injection pump calibrated at 220 hp with the as-received engine horsepower and smoke data, the horsepower is seen to be essentially the same from 1500 to 2100 rpm. The smoke measurements for the pump calibrated at 220 hp were about 2 to 3 percent higher than the as-received engine. The acceleration results indicate only a slight increase in smoke between the 185- and 200-hp engine setting. There was, however, a noticeable increase in exhaust smoke during the acceleration from 5th through 10th gears between the 200- and 220-hp pump settings. The increase appeared to be approximately 50 to 80 percent in magnitude. Comparing the as-received acceleration smoke with the calibrated 220-hp smoke readings, approximately the same level of smoke was obtained, the calibrated 220-hp readings being 1 to 5 percent absorbance greater with the calibrated 220 hp versus the as-received 220 hp. Tables 30 through 33 of Appendix A show the individual smoke evaluation summaries for the NH-220 powered truck-tractor with the injection pump preset for various engine power. Each of these tables presents the maximum, minimum and average PHS smoke readings in percent absorbance for each of the five constant speed operating conditions as well as the acceleration in 5th through 10th gears. Also tabulated are the vehicle horsepower output and speed measured during operation on the chassis dynamometer.

In summary, in the derating experiments with the Cummins NH-220 powered truck-tractor power, output did appear to have an important effect on exhaust smoke. These experiments confirm the effect of engine power on exhaust smoke from the NH-220 obtained during Part I. As the fuel rate was increased with the test bed Cummins NH-220, only a slight effect was noticed until the fuel rate reached a sufficient level. Then, the smoke tendency greatly increased. This was noticed when operating the Cummins NH-220 at 220-hp setting versus the calibrated 200-hp setting. Comparing the smoke data at 220 hp with the ten-truck variability results in the Part I final report, the smoke level was essentially the same as the overall average of the ten trucks during the constant speed operation. The smoke levels during the acceleration appeared to be approximately 4 to 5 percent absorbance less than the overall average of the ten trucks but were within the spread of the ten trucks' acceleration data.

C. Mack END-673P Engine Results

For this investigation, a Mack cab-over, single-drive axle tractor powered by a Mack END-673P, naturally aspirated, six-cylinder, inline, four-cycle diesel engine nominally rated at 187 hp at 2100-rpm engine speed was obtained. A description of this engine and vehicle, known as engine Code C, may be found on Table 1 of Appendix A. This engine used a Bosch APE 6BB injection pump and Bosch fuel injectors. The remainder of the driveline included a Mack Unishift, ten-speed transmission and a single-speed rear axle.

The odor evaluation conditions employed during this part of the engine derating study are shown on Table 34 of Appendix A. Insofar as possible, the conditions employed were identical to those used for the Cummins and Detroit Diesel powered tractors, engine Codes B and A, and contained on Table 2 of Appendix A. Since this particular make truck was equipped with a single-drive axle, it was agreed that the maximum single-axle inertia capability would be employed. Accordingly, two inertia wheels, normally used with municipal buses, were employed to simulate 25,000 lb of vehicle weight. This represents 7000 lb of inertia simulation less than that employed with the tandem drive axle Cummins and Detroit Diesel powered trucks. It was necessary to operate the tractor in 9th gear instead of 7th gear during the two constant speed conditions at 1700 and 2100 rpm in order to increase the water brake speed and obtain sufficient power absorption. Since the Mack END-673P engine produces nominally 187 hp at 2100 rpm instead of 220 hp at 2100 rpm (as was the case for the Cummins and Detroit Diesel engines) the resulting vehicle load was less during the cruise conditions than that previously available. These changes are indicated in Table 35 of Appendix A which lists the constant speed diesel odor quality/intensity procedure for the single-drive axle Mack tractor. During the procedure used to measure odor from the hot-idle condition described in Table 36 of Appendix A, it was necessary to operate for 1 min in 9th gear at 43 mph and 1900-rpm engine speed prior to the idle condition, instead of 8th gear at 37 mph. No important changes, except for the 25,000-lb vehicle weight inertia simulation on the single-drive axle were made to the idle-acceleration, acceleration or constant speed-deceleration procedures shown on Tables 37, 38 and 39 of Appendix A, respectively.

The basic plan involved for the derating experiments with the Mack tractor was to evaluate the smoke and odor emissions from the vehicle with the engine pump adjusted to standard conditions at a partially derated condition, and at a derated condition. To do this, the Mack truck recommendation of adjusting the Bosch APE 6BB fuel injection pump, rack extension distance, cam angle, and gap were employed. These adjustments were made after a Vehicle Emissions Laboratory technician was properly trained by the Service Manager of the local Mack Truck dealership. The engine derating technique involved removing the governor body cover and using a depth micrometer, a 90-deg cam angle template, and a preground cam gap clearance gauge to perform the needed adjustments. With the throttle linkage disconnected and secured in the full-rack position, the depth micrometer, set to a predetermined position, was inserted into the end of the rack extension cover, and derating accomplished. Although the rack extension dimension was changed, the cam angle and cam gap were maintained by readjustment to the factory specifications for injection pump series number 313GC4132, obtained from the local Mack distributor. This derating method was effective in changing both the torque and power curves.

Listed below are the various engine derating experiments conducted for the evaluation of the exhaust odor:

Date Conducted	Injection Pump Calibration	Vehicle Power Output, obs hp at 2100 rpm
November 30	Initial standard	150
December 1	Derated	122
December 4	Derated	122
December 5	Final standard	155

The odor results are contained in Tables 40 through 45 of Appendix A and are grouped similar to the results presented for the Detroit Diesel and Cummins powered vehicles. Since this was the first time that a Mack powered vehicle had been evaluated under the conditions identified during the Part I study, it was felt that the odor evaluations should be conducted on a back-to-back basis on two separate occasions. As shown in the above schedule of tests, odor was measured for the engine at standard conditions on November 30 and for a substantially derated engine on the following day. This first 2-day period of standard and derated odor evaluations was called the initial evaluation. Odor was again evaluated on December 4, under the same derated condition used on December 1. The engine power output and pump setting was then readjusted to standard and the odor reevaluated. The odor measurements obtained on December 4 and 5 constitute the final evaluation.

Shown on Table 40 of Appendix A is a comparison of the initial standard versus derated engine odor results. The comparison was made on the basis of the overall numerical average of the four-run judgments by the ten-person odor panel under each of the six operating conditions. From Table 40, it can be seen that the derated engine appeared to have lower overall "D" - diesel composite under operating conditions I, II, V, and VI, the cruise, acceleration, and deceleration conditions. Differences were also noted under these conditions for the four quality standards ("B" - burnt-smoky, "O" - oily, "A" - aromatic-aldehydic, and "P" - pungent). The greatest difference found for the "D," "B," "O," "A," and "P" ratings appeared to occur at maximum power in 1700 rpm, 9th gear, in which the standard engine rating of "D"-4.3 was effectively reduced to "D"-2.6 for the derated engine. The extent of the derating was approximately 21 hp for the 1700-rpm engine speed from 135 to 144 hp. Under operating condition I, the "B" ratings changed from 1.2 for the standard engine to 0.7 for the derated engine. Small changes were also evident for the "O," "A," and "P" qualities.

The "D" rating was reduced from 4.3 to 2.9 for the standard versus the derated engine, a net reduction of 1.4 for operating condition II, the 2100-rpm, constant speed condition. Similar reductions, though slightly less in magnitude to the 1700 rpm, were noticed for the "B," "O," "A," and "P" qualities. Operating conditions III and IV, the hot-idle and idle-acceleration conditions, respectively, appear to show negligible reductions in odor intensity and quality in favor of the derated engine. Under conditions V and VI, the acceleration and constant speed-deceleration conditions, the derated engine odor was slightly less than the standard engine odor. This was reflected mainly by the "D" composite ratings of 3.6 versus 2.9 (operating condition V) and 4.2 versus 3.3 (operating condition VI).

The "B," "O," "A," and "P" odor qualities represent a very slight reduction for the derated engine versus the standard engine. Summarized on Tables 42 and 43 of Appendix A are the average panel responses with the engine adjusted for standard and derated power conditions, respectively. Each of these summary tables is based on five tables of data which illustrate the panel response distribution for each of the twenty-eight runs conducted in random order, twenty-four runs with exhaust sample and four runs without exhaust (blank). The "D" - diesel and "B," "O," "A," and "P" quality standard results are shown on Tables 41A through E for the engine adjusted to standard conditions and on Tables 42A through E for the derated engine.

Shown on Table 43 of Appendix A is a comparison of the final odor evaluation conducted on December 4. The December 5 evaluation was as close as possible to the November 30 initial evaluation. As shown on Table 43, a reduction in perceived odor quality and intensity under conditions I and II was found, confirming the differences noted during the initial evaluation. Note the reduction in "D" rating from 4.1 to 2.8 for condition I with the derated relative to the standard engine. This overall "D" reduction was also evidenced by the "B," "A," and "P" ratings and somewhat by the "O" rating. The net change obtained during operating condition II was 0.5 less than the 3.5 "D" rating for the standard engine. Changes in "P" and "A" were also found. During conditions III and IV, the idle and idle-acceleration, the derated engine appeared to produce slightly greater odor, particularly during the idle. The odor from the derated and standard engines was essentially the same during conditions V and VI, the acceleration and deceleration. The comparisons on Table 43 were made from data summarized on Tables 44 and 45. Please refer to Tables 44A through E for the response distribution for each of the twenty-eight runs for the "D," "B," "O," "A," and "P" ratings, respectively. For the panel response distribution for the final evaluation under standard engine conditions, please refere to Tables 45A through E in Appendix A.

In summary of the initial and final odor evaluations, engine derating appeared to have an effect on odor under certain operating conditions. Comparing the net changes on Table 43 with Table 40, fairly consistent reductions in odor quality and intensity were found during conditions I and II, the 1700- and 2100-rpm engine operation. Derating had little effect on odor for conditions III and IV, the idle and acceleration. Although a reduction in odor was determined under conditions V and VI initially, little change was noted during the final evaluation. A review of the four qualities, "B," "O," "A," and "P" showed that on the basis of obviousness, the "B" - burnt-smoky was most obvious under all operating conditions during the 4 days of operation, regardless of engine power. This was generally true for the "O" - oily, "A" - aromatic-aldehydic, and "P" - pungent qualities in being the second, third, and fourth most obvious, respectively. Comparing this with other diesel powered trucks, the "B" - burnt-smoky rating most obvious with the Mack, represents a reversal over the ratings obtained with the Cummins powered tractor. With the Cummins NH-220 tractor, the "A" - aromatic and "O" - oily ratings were generally most obvious. In a way, the order of obviousness noted with the Mack vehicle was nearer to the two-cycle bus and truck ratings that have been obtained in which the "B" is always most ovbious, followed by "O" and "A, " with "P" being the least obvious. Although the order of obviousness with the Mack was similar to that obtained with the two-cycle type engine, the odors were found to be very light in the burnt-smoky quality. The panel reported the odors to be rather sweet and not very pungent. Some of the odors were similar to spices, and others had a distinguishable odor similar to certain medicines.

Measurements were also made of smcke intensities using the PHS smokemeter. These smoke measurements were made with the vehicle in the standard, under a partially derated, under a derated, and in a final standard condition according to the following schedule:

Date Conducted	Injection Pump Calibration	Vehicle Power Output, obs hp at 2100 rpm
November 29	Partially derated	135
November 29	Initial standard	150
December 1	Derated	122
December 5	Final standard	155

The smoke evaluation conditions were essentially the same as those used with the Cummins and Detroit Diesel powered trucks and are listed on Table 46 of Appendix A. One difference was the use of 25,000-lb inertia simulation for the single-axle Mack tractor instead of 32,000-lb inertia simulation used with tandem drive units. Since the nominal power output of the Mach END-673P is 187 hp, as compared to 220 for the Cummins NH-220 and Detroit Diesel 6-71 N engines, an adjustment had to be made in the road load setting preset in the dynamometer and retained during the acceleration through the gears.

Shown on Table 49 of Appendix A and repeated in the text as Table 5 is an overall summary of the smoke measurements obtained. The constant speed operating conditions, A through F, are listed first, followed by condition G, the acceleration from 5th into 6th into 7th into 8th into 9th into 10th gear with 30 mph preset in the water brake dynamometer and retained during the acceleration. All of the constant speed operation was at open-rack, maximum power output in 9th gear. On November 29, 1967, the vehicle was operated with the pump adjusted for standard engine power output and resulted in smoke readings from 7- to 13-percent opacity for the 1300- to 2200-rpm speed range. The pump was then adjusted to produce 135 hp at the rear wheels at 2100-rpm engine speed, and the smoke readings ranged from 4- to 6-percent opacity. On December 1, the engine was further derated to result in 122-hp vehicle output at 2100-rpm, and the smoke readings further reduced to a range of 1.5- to 5.5-percent opacity. On December 5, the injection pump was returned to the initial standard condition and resulted in a smoke emission, under constant speed conditions, from 6- to 12.5-percent opacity. The final standard vehicle output was 155 hp instead of the 150 hp recorded during the initial investigation. The initial and final smoke readings with the engine adjusted for standard power were about the same. Shown on the lower portion of Table 49 is a summary of the smoke readings

TABLE 5. OVERALL SUMMARY OF THE EFFECT OF DERATING A MACK END-673P POWERED TRUCK-TRACTOR ON EXHAUST SMOKE

Vehicle: Mack Tractor 39946
Engine: Mack END-673P

Operating Conditions: See Table 46 of Appendix A
Fuel: EM-29-F (No. 2 Diesel)

Date: 11/29/67 11/29/67 12/1/67 12/5/67

Constant Speed (All open rack - maximum power output)

		Injector Pump Calibrated for Conditions							
		Initial Standard		Partially Derated		Derated		Final Standard	
Operating Conditions	Engine Speed, rpm	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %	Hp	Smoke, %
A	1300	100	7.0	92	4.0	80	1.5	102	6.0
B	1500	114	8.0	110	3.0	93	2.0	116	7.0
C	1700	132	10.5	130	4.0	114	2.5	138	10.0
D	1900	143	11.5	130	4.0	122	2.5	146	11.0
E	2100	150	12.0	135	5.0	122	4.0	155	11.0
F	2200	152	13.0	140	6.0	120	5.5	156	12.5

Date: 11/29/67 11/29/67 12/1/67 12/5/67

Acceleration (30 hp at 30 mph preset and retained)

Operating Conditions	Transmission Gear No.	Initial Standard Smoke, %	Partially Derated Smoke, %	Derated Smoke, %	Final Standard Smoke, %
G	5th	10.5	6.0	4.5	10.0
G	6th	12.5	6.5	6.0	11.0
G	7th	13.0	7.0	5.5	11.5
G	8th	13.0	7.0	6.0	12.0
G	9th	12.5	6.0	6.0	12.0
G	10th	13.5	5.0	2.5	11.0

obtained during condition G, the acceleration from 4th into 10th gears. The maximum average smoke readings obtained appeared to be consistent for each engine rating, regardless of the gear range in which the vehicle was operated. For example, the partially derated smoke, conducted on November 29, ranged from 5- to 7-percent opacity. The smoke output under the derated condition ranged from 2.5- to 6-percent opacity. The initial and final standard smoke readings seemed to agree fairly well and ranged from 10.5- to 13.5- initially and 10- to 12-percent opacity during the final tests. The summarized results of Table 49 are listed in detail on Tables 50 through 53 of Appendix A. Each of these tables is organized to present the maximum, minimum, and average PHS smoke readings in percent opacity for the seven constant speed, maximum power conditions and the acceleration in 5th through 10th gears. Also tabulated are the vehicle horsepower and speed measurements obtained. In summary of the engine derating experiments with the Mack tractor, engine power output appeared to have an important effect on vehicle exhaust smoke.

D. Summary

In summary of the experiments with engine derating on exhaust odor and smoke, the following was found based on the single engine of each type and make employed. For the Detroit Diesel 6-71 N engine, derating had little effect on smoke or odor emissions. The lack of reduced smoke under derated conditions was attributed to the relatively low smoke level with the particular engine employed at rated power. Derating the Cummins NH-220 engine reduced the measured smoke output, especially the initial step of engine derating from 220 to 200 hp at 2100 rpm. The derating to 180-hp from 200-hp level was not as pronounced because of the relatively light smoke output obtained at the 200-hp level. Derating of this four-cycle engine had no noticeable effect on odor. Although valid only for the engines investigated, the odor levels were sometimes the same for the two-cycle and four-cycle Cummins engine. This was found during operation at 1700- and 2100-rpm engine speed for certain odor qualities. The oily and aromatic qualities, however, were slightly higher during these two conditions for the four-cycle powered tractor than the two-cycle powered tractor. The "O" oily quality of the Cummins four-cycle exhaust seemed more prevalent in relation to the "B," "A," and "P" than with the two-cycle engine results. The two-cycle engine data represented a much weaker characteristic two-cycle odor, and the "B" burnt quality was always the most obvious. This was similar to the results obtained with the two-cycle powered bus during Part I.

The only instance in which power rating appeared to have a noticeable effect on vehicle odor was with the one Mack tractor investigated. The exhaust odor from this four-cycle engine was slightly higher than the other two engines investigated. When considering the qualities and the obviousness of the qualities relative to other diesel exhausts evaluated, the improvement noticed with this one engine under the two constant speed conditions may not justify engine derating as a desirable technique for odor reduction. For derating to be useful and acceptable, it should be successful in most, if not all, of the evaluation conditions employed, not in one or two of the six conditions. The effect of derating, however, was pronounced in reducing visible exhaust smoke. This reduction was in good agreement with that determined for the Cummins NH-220 engine and with previous experience. In conclusion, the effectiveness of diesel engine derating on smoke and ineffectiveness on odor was demonstrated on three single representative types of engines under identical operating conditions.

IV. FLEET TEST OF SMOKE SUPPRESSANT ADDITIVE

The objective of this test was to determine the effectiveness of a smoke suppressant additive on the visible smoke discharge from diesel powered intercity truck-tractors. The test was limited to one widely used type of diesel truck, namely, a tandem drive axle, cab-over tractor powered by a Cummins NH-220 naturally aspirated, four-cycle engine.

A. Preparations

The pretest preparations included the selection of a suitable test fleet, determination of the additive, treatment level and method, and the approach to be used to measure the effectiveness of the additive in service. During the Part I vehicle variability studies, a fleet of five identical International Harvester cab-over truck-tractors was located. Each tractor was powered by a similar Cummins NH-220, naturally aspirated, four-cycle diesel engine, through a Fuller RT9-10, ten-speed, Road Ranger transmission and tandem drive Eaton single-speed rear axle. This fleet of five tractors is normally involved in fuel hauling at the Howell Refinery, a local San Antonio refiner of commercial and special fuels. This fleet of tractors was in unusually severe highway operation involving a minimum of 6 days per week--two shifts per day--of liquid transport. In routine transport of liquid petroleum products to and from the refinery, these identical tractor-trailer transport rigs were usually loaded to the maximum limit of 72,000-lb gross vehicle weight. The type of service as well as the mileage accumulation, approximately 12,000 miles per month under fuel and engine stressing conditions, tended to make this group of trucks ideal for the proposed fleet test.

An additional and important feature was that the majority of fueling and maintenance was in San Antonio, the home base and turn-around point. On February 14, 1967, the Project Officer was informed of the availability of the five-truck fleet and the many advantages. With the consent of the Project Officer, a suitable arrangement was negotiated with Howell Refining Company for utilization of the five-truck diesel fleet in the test of the smoke additive. Additional description of the Howell Refining vehicles and engines may be found in Table 1 of Appendix B. All five trucks were essentially identical not only in tractor and engine specifications but in drivelines, rear axle and tire size.

At the request of the Project Officer, six 55-gal drums of fuel additive were obtained. The additive, a barium-containing smoke suppressant material, was commercially available and already in use in some regions of the United States. The additive manufacturer was requested to recommend an average dosage level to be used in treating the normally used number 2 diesel fuel, as well as the method of treatment. On the basis of direct addition of the additive to the tractor saddle tanks, it was recommended that the additive, prediluted in equal parts of kerosene to promote mixing, be added at the rate of 1/2 percent by volume of the base fuel. Average treatment level of the undiluted additive was 1/4 percent by volume of the base fuel.

A system was devised whereby Vehicle Emissions Research Laboratory technicians periodically supplied quart and pint containers marked for addition to "10 gal," "20 gal," "30 gal," "40 gal," and "50 gal" for use during truck refueling. Each group of cans contained the correct amount of additive to permit simple addition to the fuel tanks after refueling. To illustrate, if 50 gal of fuel were added to the vehicle fuel tank, a full 1-qt can of additive was poured in on top. According to the manufacturer, this additive would satisfactorily mix within the saddle tanks due to movement on the highway and due to fuel return from the engine. The driver supervisor, as well as the truck drivers, was instructed to add the correct quantity of smoke suppressant additive and to carry several containers with them in the cab for use when refueling away from San Antonio.

The approach followed was to place each tractor on test by measuring the smoke with and without the additive-treated fuel. The PHS smokemeter and the chassis dynamometer procedures established during the Part I program were employed. As agreed with the Project Officer, it was desired to simulate what a fleet operator might do if he decided to begin using a smoke suppressant material along with his normal fuel supply. Therefore, no premaintenance of the engine, over and above which was normally accomplished under the usual fleet maintenance program was performed. Because of the high use-rate of these tractors and the lack of suitable pump-off type rental tractors for use by the Howell Refining Company, it was necessary to evaluate the smoke emissions with and without the treated fuel on Sundays when the tractors were not generally in operation. Steady state, open-rack, maximum power, engine smoke measurements were obtained in triplicate at 1700-, 1900- and 2100-rpm engine speeds in 7th gear. In addition, an open-rack acceleration throughout gears 5 through 10 was performed. These operating conditions are listed in Table 2 of Appendix B. Detailed operating and measurement procedures for the constant speed conditions and idle-acceleration through the gears are described in Tables 3 and 4 of Appendix B. Daily records were kept of vehicle mileage, as well as pertinent maintenance information. It was not planned, however, to intentionally remove the injectors prior to the beginning of this 6-month fleet test since the effect of the additive on engine maintenance, cleanliness, and wear had already been published. It was planned to measure the smoke and vehicle performance prior to the start of the program using an untreated number 2 fuel and with the treated fuel on a back-to-back basis. At intervals of approximately 2 months, each truck would be retested, first with the treated fuel and then with the untreated, number 2 material. For the 6-month fleet test, this meant back-to-back tests at 0, 2, 4, and 6 months of operation.

B. Results

This fleet test, begun on April 2, 1967, was successfully completed on October 15, 1967, for an overall total period of 6 months. Shown in Table 6 are the pertinent mileage maintenance records as well as the mileage accumulated since the start of the test for each of the five tractors. From this table, it may be noted that each tractor accumulated over 70,000 miles during the 6-month period except for Truck 286 which accumulated 66,885 miles. Tractors 282, 283 and 284 accumulated the highest mileage for an average rate of over 12,000 miles per month.

TABLE 6. FLEET TEST VEHICLE MILEAGE DATA

(End of 6 Months of Operation)

Howell Tractor No.	Model* Year	Date Test Began	Tractor Mileage As of Date Test Began	Tractor Mileage Since Last Injector Change	Total Test Miles (End of Test)
282	1964	4/2/67	392,625†	102,977	73,199
284	1965	4/2/67	322,981	138,608	74,357
283	1965	4/9/67	375,410	107,099	73,978
286	1966	4/9/67	181,249	113,755	66,885
285	1965	4/11/67	364,395‡	77,651	70,772**

---

*All truck-tractors are International Harvester Model DCOF-405 units except Tractor 286 which is a Model DCOF-400D.

†Major engine overhaul performed at 207,944 miles (including rings, valves, bearings, injectors, etc.).

‡Major engine overhaul performed at 357,207 miles (including rings, valves, bearings, injectors, etc.).

**Middle head (cylinders 3 and 4) removed and gasket replaced on Truck 285, on August 6, 1967, at 47,120 test miles.

The smoke inspection results, summarized on Table 7, show that the smoke suppressant additive was effective in reducing exhaust smoke. The data on Table 7 are arranged by truck number and show the initial, 2-month, 4-month and final smoke inspection results chronologically for each truck-tractor. For Tractor 282, the additive was successful in reducing the visible smoke to about one-fourth the level measured with untreated fuel and nearer one-third, as shown by the final smoke

TABLE 7. OVERALL SUMMARY OF SMOKE INSPECTION RESULTS FOR FLEET TEST OF SMOKE SUPPRESSANT ADDITIVE

Engine: Cummins NH-220 naturally aspirated

				Constant Conditions						Transient-Acceleration Conditions					
				1700 rpm		1900 rpm		2100 rpm		PHS Smokemeter Reading, % in Gear No.					
Truck No.	Test Miles	Date Inspected	Test Fuel	Smoke*	hp†	Smoke	hp	Smoke	hp	5th	6th	7th	8th	9th	10th
282	0	4/2/67	Reference	26	160	27	160	29	160	20	25	27	27	25	33
			Additive	7	160	6	160	5	160	9	10	9	8	10	13
			Difference	19	-	21	-	24	-	11	15	18	19	15	20
	29,684	6/4/67	Reference	25	150	25	160	27	160	19	22	24	24	24	29
			Additive	6	150	7	160	7	160	7	8	9	8	6	6
			Difference	19	-	18	-	20	-	12	14	15	16	18	23
	49,106	8/6/67	Reference	24	160	26	160	26	150	21	24	25	27	28	33
			Additive	6	160	6	160	7	150	8	6	8	8	6	15
			Difference	18	-	20	-	19	-	13	18	17	19	22	18
	73,199	10/15/67	Reference	36	160	33	160	31	165	24	30	31	32	36	37
			Additive	10	160	9	160	8	165	10	11	11	11	10	14
			Difference	26	-	24	-	23	-	14	19	20	21	26	23
283	0	4/9/67	Reference	23	140	23	140	24	140	27	24	23	24	26	39
			Additive	8	140	7	140	7	140	11	9	9	9	9	15
			Difference	15	-	16	-	17	-	16	15	14	15	17	24
	28,725	6/18/67	Reference	25	140	23	150	24	160	21	21	23	25	24	26
			Additive	12	140	6	150	5	160	8	7	7	7	8	15
			Difference	13	-	17	-	19	-	13	14	16	18	16	11
	50,831	8/15/67	Reference	36	150	33	160	30	165	21	23	24	26	34	44
			Additive	17	150	11	160	7	165	11	9	9	9	17	33
			Difference	19	-	22	-	23	-	10	14	15	17	17	11
	73,978	10/15/67	Reference	30	150	28	160	26	165	21	24	25	25	30	41
			Additive	17	150	12	160	8	165	10	10	10	11	15	23
			Difference	13	-	16	-	18	-	11	14	15	14	15	18
284	0	4/2/67	Reference	32	160	31	160	31	160	36	35	34	33	33	30
			Additive	8	160	7	160	6	160	10	10	10	8	7	15
			Difference	24	-	24	-	25	-	26	25	24	25	26	15
	24,877	6/4/67	Reference	29	150	31	160	33	160	30	30	30	31	27	28
			Additive	11	150	12	160	15	160	17	18	20	19	12	11
			Difference	18	-	19	-	18	-	13	12	10	12	15	17
	48,826	8/6/67	Reference	30	150	34	160	35	160	25	25	31	33	31	22
			Additive	6	150	6	160	8	160	7	11	11	11	6	6
			Difference	24	-	28	-	27	-	18	14	20	22	25	16
	74,357	10/1/67	Reference	29	150	33	160	33	160	24	31	32	34	31	23
			Additive	6	150	6	160	7	160	8	8	8	7	5	3
			Difference	23	-	27	-	26	-	16	23	24	27	26	20
285	0	4/11/67	Reference	16	140	19	140	23	140	17	23	22	22	17	15
			Additive	6	140	8	140	11	140	12	12	12	11	6	5
			Difference	10	-	11	-	12	-	5	11	10	11	11	10
	23,485	6/11/67	Reference	29	140	26	150	27	160	24	25	26	27	24	29
			Additive	6	140	6	150	7	160	8	9	8	8	6	8
			Difference	23	-	20	-	20	-	16	16	18	19	18	21
	47,381	8/13/67	Reference	15	150	15	160	18	160	12	14	13	15	15	17
			Additive	3	150	3	160	5	160	5	5	5	5	5	5
			Difference	12	-	12	-	13	-	7	9	8	10	10	12
	70,772	10/8/67	Reference	13	150	13	160	14	165	10	12	13	14	12	14
			Additive	6	150	7	160	9	165	6	7	7	7	5	4
			Difference	7	-	6	-	5	-	4	5	6	7	7	10
286	0	4/9/67	Reference	38	150	34	150	32	160	30	28	28	31	37	41
			Additive	15	150	11	150	12	160	16	14	17	18	19	23
			Difference	23	-	23	-	20	-	14	14	11	13	18	18
	24,800	6/11/67	Reference	46	140	41	140	40	150	38	37	38	40	44	46
			Additive	31	140	26	140	26	150	25	26	27	28	35	37
			Difference	15	-	15	-	14	-	13	11	11	12	9	9
	47,261	8/13/67	Reference	11	140	10	140	12	150	11	11	10	11	9	11
			Additive	4	140	3	140	4	150	7	6	4	4	3	5
			Difference	7	-	7	-	8	-	4	5	6	7	6	6
	66,885	10/8/67	Reference	32	140	33	150	33	160	33	35	38	39	38	28
			Additive	14	140	14	150	14	160	16	16	16	17	15	14
			Difference	18	-	19	-	19	-	17	20	22	22	23	14

---

*Percent light absorbance, PHS meter 5-1/2 in. above tip of stack.
†Maximum power, open-rack engine operation in 7th gear.

inspection. The additive was effective in cutting the smoke emissions during both constant speed conditions of 1700, 1900 and 2100 rpm, as well as during the acceleration condition from 5th into 6th into 7th into 8th into 9th and into 10th gear.

The smoke from Tractor 283 was also reduced to about one-third of the level measured with untreated fuel when treated with the additive material. This level of improvement or smoke reduction remained steady throughout the 6-month program and was noted under both constant speed conditions and the transient acceleration condition. The smoke emissions from Tractor 284 were reduced during the constant speed conditions to one-fourth of that measured when untreated fuel was used. The level of smoke reduction was not as great during transient conditions, being about one-half to one-third of that typically obtained with untreated fuel. Throughout the 6-month test, the smoke emissions from Tractor 285 appeared to be cut by more than half, sometimes to one-fourth, of what they were with untreated fuel. The greatest reduction seemed to occur after 23,485 miles, at the first interim inspection, after 2 months of operation. The constant speed and acceleration conditions indicated a substantial reduction in exhaust smoke tendencies.

The fifth truck involved in this fleet test, Truck 286, also showed a marked reduction in smoke output when the barium containing additive was used. Although the amount of reduction was not as great with Truck 286 as with the other four tractors in the fleet, the reduction was generally at least 50 percent or more, and sometimes the smoke was reduced to about one-third of the level measured with untreated fuel. An interesting and as yet unresolved set of smoke measurements was obtained at the end of 4 months of operation, on August 13, 1967, after 47,261 test miles. The untreated smoke output of this tractor had routinely varied between 30 and 40 percent absorbance during the initial smoke test and after 2 months of operation. The smoke measurements obtained after 4 months of operation, however, showed that the base fuel smoke, for some unknown reason, had changed to 10 to 12 percent absorbance instead of the 37 to 46 percent absorbance previously measured. The smoke measured with the additive treated fuel still showed a marked and even more substantial reduction in smoke working from the lower baseline.

According to the fleet operator, the Howell Refining Company, and their driver personnel, no changes or modifications had been made in fuel pump or engine adjustment and no repair or maintenance other than the normal preventative maintenance conducted. According to the power measurements obtained at the end of 4 months, it may be noted that the tractor output remained at about 140 hp at 1700 and 1900 rpm, and 150 hp at 2100 rpm. No noticeable or outward change in vehicle operation could be found, and the lower than usual smoke measurements with both reference and additive fuels were confirmed by repeat tests. The final smoke measurement and inspection made on October 8, 1967, at the end of 66,885 miles, indicated that the smoke output of this tractor had resumed the level that was measured at the beginning of the test, namely, about 32 to 38 percent absorbance. Regardless of the smoke output from this tractor fueled with untreated number 2 diesel, the smoke was always reduced by at least 50 percent when the treated fuel was used.

Contained in Tables 5 through 24 of Appendix B are the vehicle smoke evaluation summaries for each of the five tractors evaluated. These summaries list the operating data, as well as the maximum, minimum and average PHS smoke readings obtained under additive fuel and untreated fuel conditions for both the constant speed and the acceleration procedure. Operating data such as tractor output and tractor speed are also included for the constant speed condition. The results for the additive treated, Howell number 2 diesel fuel are listed first, followed by the smoke inspection data for the SwRI Code EM-29-F commercial number 2 diesel fuel used as a reference base fuel for comparative purposes. Tables 5 through 9 list the initial smoke inspection results, and Tables 10 through 14 list the results after 2 months of operation. Tables 15 through 19 of Appendix B contain a summary of the smoke inspections conducted after 4 months of fleet test. The data listed in Tables 20 through 24 were obtained during the final 6-month smoke inspection. Table 20 lists the results for Tractor 284 evaluated on October 1, 1967, at 74,357 test miles. Tables 21, 22, 23, and 24 contain the results for Tractors 282, 286, 283 and 285, respectively. These tables are included as supporting data for the information summarized and shown in the overall summary of Table 3 in the text.

On August 6, 1967, at 47,120 test miles, the middle head (cylinders 3 and 4) was removed from Truck 285. The purpose for removing the head was to replace the head gasket and eliminate a small water leak. Because of the extremely high use rate of these five diesel powered tractors, the head was removed and the gasket replaced before notice could be given and photographs of the combustion chamber and piston tops obtained. Visual inspection, however, indicated light gray to white combustion chamber deposits instead of the black-dark gray carbon deposits normally seen. The deposits appeared to have stabilized and were adjudged to be moderate to light in thickness and accumulation. This has been reported by the manufacturer as the characteristic color and appearance of a combustion chamber in which the barium containing smoke suppressant additive has been operated (Ref. 4). Also worthy of mention is the fuel pump calibration performed on the PT type Cummins pump on truck number 283. The recalibration was conducted on July 21 at 36, 257 miles of test operation. The effect was to increase the maximum power output approximately 10 hp at 1700, 1900 and 2100 rpm. There was no other reported maintenance conducted on the five engines involved during the 6-month fleet test. It was fortunate that no major engine overhaul or engine modification, repair or adjustment was required during the course of the 6 months of operation, nor was an "overhead" (requires removal, repair, and calibration of fuel injectors and adjustment of the exhaust valves) performed. This is felt somewhat abnormal for five tractors to complete well over 70, 000 miles each, under the type of engine and fuel stressing operating conditions experienced. As previously mentioned, the Howell Refining fleet typically operates full both ways, in which crude oil is hauled to the refinery and finished petroleum products are hauled to the consumer. This means that for the mileage accumulated, which was 2000 to 3000 miles per month greater than is generally obtained with similar fleets, the engine and vehicle are operating under loaded, maximum power, conditions more often than would be the case with a freight hauler or a bulk hauler that returned empty. Being a constant density type hauling operation, the gross vehicle weight allowed in Texas of 72, 000 lb was generally the rule. The apparent maintenance policy at Howell regarding "overheads" was on an as-needed basis by the individual vehicle. As noted on Table 6, the mileage since injector change was over 100, 000 miles for all trucks except Tractor 285 which was 77, 651 miles. The absence of maintenance in this category may or may not have been the result of the additives' claimed improvement on injector deposits, fouling and cleanliness properties. This fleet test was limited in this respect as injectors, and engine parts such as heads, valves and pistons were not periodically inspected, examined, and related to a similar truck operating with untreated fuel.

C. Summary

The 6-month, five-truck fleet test of a diesel smoke suppressant fuel additive was successful in demonstrating the effectiveness of this technique over an extended period. This commercially available barium-containing diesel fuel additive was successful in reducing the visible smoke from one-half to as low as one-fourth the level measured with untreated number 2 diesel fuel. The effect of the smoke suppressant additive seemed greater under the constant speed, steady state, maximum temperature operating conditions. It is not safe to conclude that the transient condition always gave higher readings than under the constant speed conditions, although there were a number of inspections which seemed to indicate this. For the overall 6-month test, including inspections at 0, 2, 4, and 6 months of operation, the additive seemed about as successful at the beginning, during and at the end of the test for each of the tractors investigated. It is not apparent that the additive was more successful at higher than at lower base smoke readings although the additive seemed to be more successful in certain tractors than in others. Finally, the results of this successful test of the barium containing additive should not be directly extrapolated to other types of engines and vehicles or to other versions of the type of equipment used during this test. The type diesel rig utilized in this study, though common and fairly widely used, represents only one type of tractor-engine-driveline system of which there are numerous others. Therefore, it is advised that the results of this fleet test be considered, judged, and utilized accordingly.

V. EFFECT OF DIESEL EXHAUST MANIFOLD OXIDATION ON ODOR AND SMOKE

During Part I, a number of different techniques involving dilution of diesel exhaust with outside air prior to its exit from the vehicle were investigated for their effect on odor and smoke. Of the three techniques subjected to experimental study and evaluation with the Cummins NH-220 engine, the exhaust manifold oxidation system appeared to have the most promise. Manifold oxidation involves introducing a small amount of air to the exhaust as it passes the exhaust valve at a point adjacent to or on top of the engine exhaust valve. The system is similar to some exhaust manifold oxidation systems employed by certain auto makers for hydrocarbon and CO reduction. Fresh air is injected at the underside of each exhaust valve in an attempt to partially or further oxidize various exhaust constituents under maximum available exhaust heat conditions. To distinguish this method, it was called the DEOX system for Diesel Exhaust Oxidation.

The initial studies of exhaust manifold oxidation were conducted with a test bed operated Cummins six-cylinder, four-cycle NH-220 engine, a popularly used diesel engine in intercity truck-tractors. The results of these initial investigations indicated that addition of fresh air at the underside of the exhaust valve noticeably reduced smoke. The experiments were conducted under maximum power output, high engine speed. Conditions of high exhaust temperature-engine heat were felt to be conducive toward further oxidation of the particulate carbon by a small amount of fresh air added as the exhaust was expelled from the combustion chamber.

Although the smoke reductions obtained with the four-cycle Cummins engine were not substantial, there was a possibility that the method might have promise in the two-cycle type engine in not only making a slight improvement in smoke but possibly in reacting one or more of the external odorants to a nonodorous condition. As recommended in the Final Report covering the previous program (Ref. 1), additional work with manifold oxidation appeared justified in the two-cycle 6V-71 engine. In discussion with the Project Officer, it was agreed that a limited investigation would be made of the diesel exhaust oxidation (DEOX) system in a Detroit Diesel two-cycle, 6V-71 powered city bus. This evaluation would be back-to-back with and without exhaust oxidation on only a single vehicle.

A. Preparations

The approach was to add the fresh air as near as possible to the combustion gases from the exhaust of a GM Detroit Diesel 6V-71 E engine installed in a municipal bus. Shown in Figure 10 is the rear or right bank of the engine as installed in a GM Truck and Coach Division Model TDH-4519, forty-five-passenger city bus equipped with hydraulic transmission. The initial experiments involved adding the oxidizing air through 0.25-in. diameter stainless steel probes. The three probes, which served the rear bank and may be seen in Figure 10 were manifolded together and supplied from a high-pressure laboratory air system. Detroit Diesel 6V-71 powered buses routinely used in San Antonio Transit buses have two exhaust valves per cylinder. These exhaust valves are located longitudinal or in-line with the crankshaft of the engine and are centered in the combustion chamber. Between each set of two exhaust valves, the unit fuel injector, which is a 60S type, is located. The head is cast so that for each cylinder the exhaust from both exhaust valves converges to a common port from which it then exits into the exhaust manifold. Since it was not possible for one probe to reach both valve underheads, the 0.25-in. diameter stainless steel DEOX air delivery tubes were inserted as far as possible in the common exhaust port. The probes, shown installed in the exhaust manifold and with the manifold removed from the cylinder head, Figures 10 and 11, respectively, necessarily were fairly short and did not fully reach the valve underhead as desired. The view shown in Figure 11 is that of the left bank or front exhaust manifold which was accessible through the rear seat of the bus. Even with the rear bumper and baffle plate removed, access to the rear or right bank manifold was extremely difficult and time-consuming for accurate positioning of the exhaust probes.

As the 1/4-in. probe system shown in Figures 10 and 11 was the simplest system to install, the preliminary tests were made with this system. Using the PHS smokemeter and operating conditions of open-rack, maximum engine power, at a number of engine speed/vehicle speed

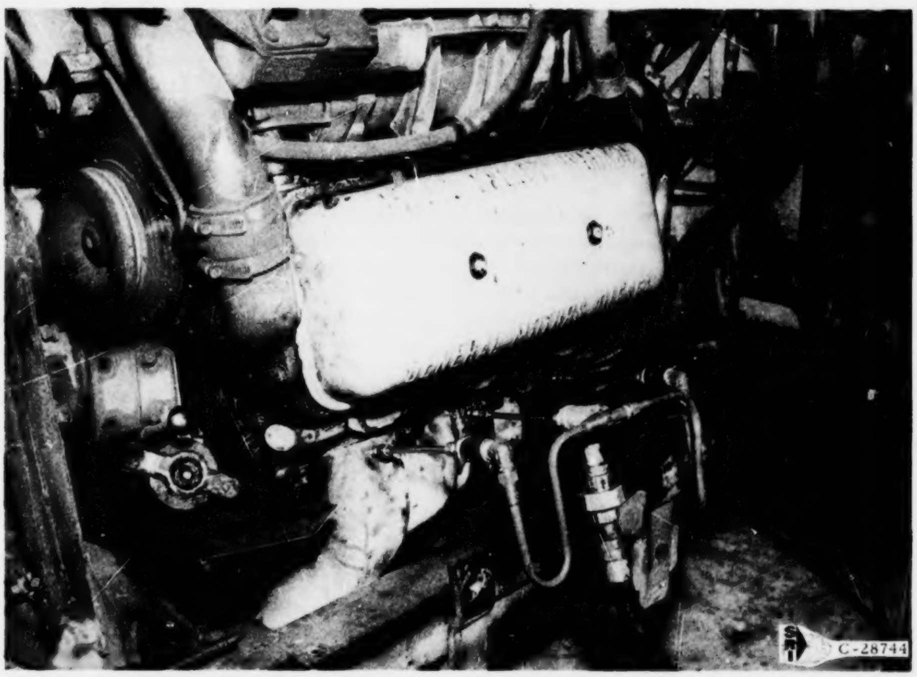
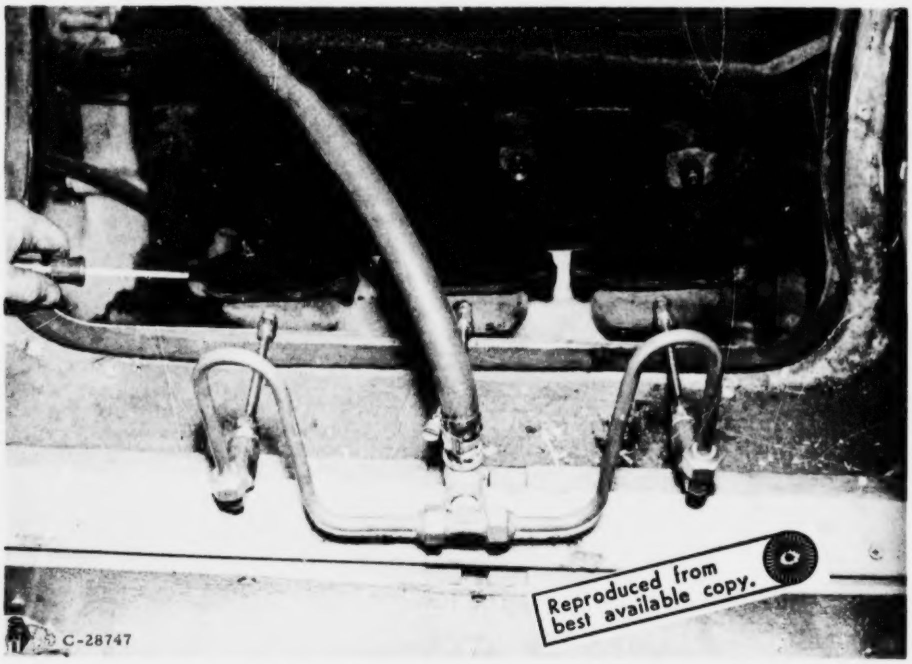


FIGURE 10. RIGHT OR REAR BANK OF DETROIT DIESEL 6V-71 E ENGINE EQUIPPED WITH EXHAUST MANIFOLD OXIDATION (DEOX) SYSTEM
(1/4-In. Injection Tubes, One per Cylinder)



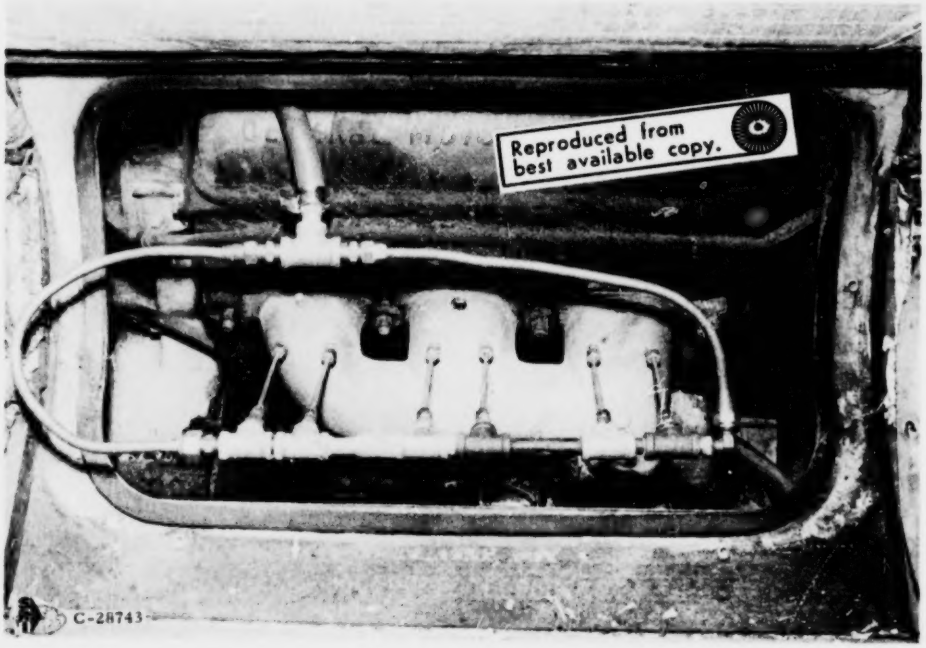
Reproduced from best available copy.

FIGURE 11. LEFT OR FRONT EXHAUST MANIFOLD REMOVED SHOWING THE LENGTH AND POSITION OF DEOX AIR DELIVERY TUBES
(1/4-In. Injection Tubes, One per Cylinder)

combinations, it was found that the DEOX system had little or no effect on the visible exhaust under all airflows investigated. At the conclusion of this initial set of experiments, it was reasoned that the DEOX system may have been ineffective due to the positioning of the air delivery probes relative to the exhaust valves. It was felt that the DEOX air was not effectively contacting the combustion gases near enough to their exit from the combustion chamber and that the temperature of the gases at the point of air injection was not as high as it could be.

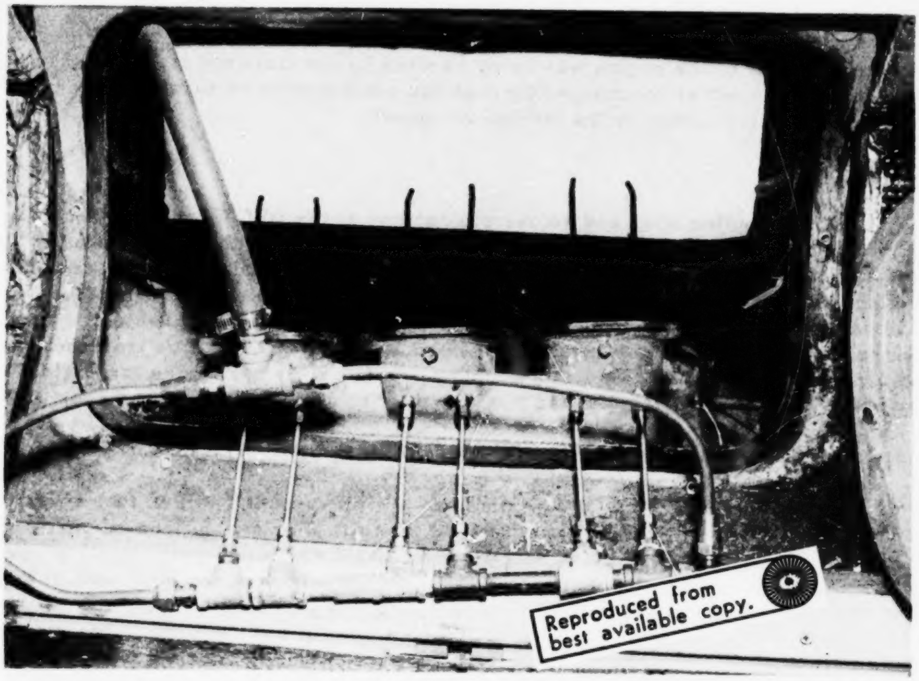
In an effort to reach these exhaust gases at their maximum temperature condition, another attempt was made. This set of experiments involved the use of one 3/16-in. diameter air injection tube for each exhaust valve. Figures 12 and 13 show this air injection system in which an air delivery probe is located at the underside of the exhaust valve. To conduct this series of experiments, it was necessary to utilize only the left or front bank, which was accessible through the rear seat opening. It was not possible, due to the rear frame member on which the engine was mounted, to install this more complicated system on the rear or right bank exhaust manifold. The installation and air delivery manifold system are shown in Figure 12. Figure 13 illustrates the DEOX system mounted in the exhaust manifold but with the exhaust manifold removed from the engine. The longer length probes that were required to reach each exhaust valve are shown in Figure 13 and may be compared with the stubby probes used in the 0.25-in. injection system illustrated in Figure 11.

Provisions were made to cut "on" or "off" the air injection system manually and to adjust the flow rate and delivery pressure as desired. This air supply system is shown in part in Figure 14 and was located at the rear of the bus. The laboratory air compressors delivered to a holding tank shown in the photograph from which the DEOX air was then supplied to the left bank of the engine. Three technicians were required during these experiments, one person to operate the vehicle, another person to operate the smokemeter and take smoke readings, and the third person to operate the oxidizing air system. Since only one bank could be practically equipped for manifold oxidation with the long reach 3/16-in. type probes, the right exhaust manifold was removed and a different design exhaust manifold installed. This permitted the exhaust from the right bank of the engine to be discharged through a separate muffler and then into the atmosphere downwind of the



Reproduced from best available copy.

FIGURE 12. LEFT OR FRONT BANK OF DETROIT DIESEL 6V-71 E ENGINE EQUIPPED WITH EXHAUST MANIFOLD OXIDATION (DEOX) SYSTEM
(3/16-In. Injection Tubes, One per Each Valve of Each Cylinder)



Reproduced from best available copy.

FIGURE 13. LEFT OR FRONT EXHAUST MANIFOLD REMOVED ILLUSTRATING THE LENGTH AND POSITION OF DEOX AIR DELIVERY TUBES
(3/16-In. Injection Tubes, One per Each Valve of Each Cylinder)

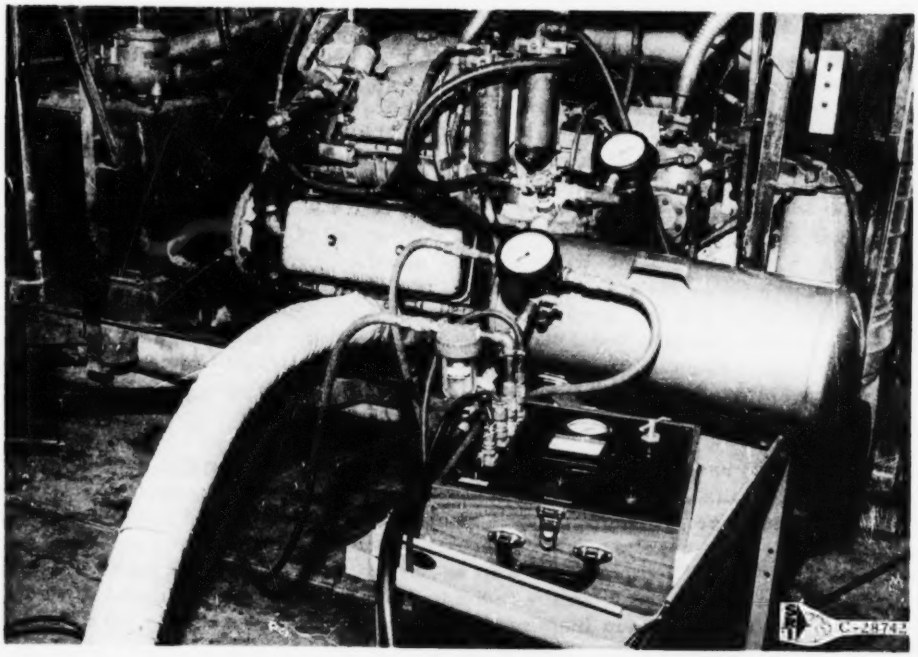


FIGURE 14. AIR DELIVERY EQUIPMENT AND PHS SMOKEMETER USED DURING EXHAUST MANIFOLD OXIDATION (DEOX) EXPERIMENTS
(Connected to Left or Front Bank of Detroit Diesel 6V-71 E Engine)

vehicle. The connecting pipe from the right bank of the engine to the exhaust muffler was plugged so that only the left bank of the engine was being handled by the standard muffler exhaust configuration. These gases were either discharged through the smokemeter or through the central stack system for odor characterization by the ten-person panel.

B. Results

The results of routine odor and smoke evaluations of the DEOX system are contained in Appendix C. The odor evaluation conditions and the operating procedures are listed in Tables 1 through 5 of Appendix C. Three constant speed conditions, a 20- and 40-mph cruise and an idle after a 30-mph cruise condition were investigated. The operating procedures for the dynamometer, vehicle and odor panel for the 20- and 40-mph conditions are contained in Table 2. The odor evaluation procedure under the engine idle condition is described in Table 3. Two transient operating conditions, an acceleration after idle and a deceleration from 40-mph cruise, are listed in Tables 4 and 5, respectively. The three cruise and two transient conditions represent modes of vehicle operation which produce significant levels of exhaust odor. For additional details on the development of these five odor evaluation procedures, please see the Part I Final Report.

The evaluation of DEOX on odor was made on a back-to-back basis in that evaluations were obtained with DEOX operative and then inoperative. For the odor evaluations, a single airflow delivery condition of 28.5 standard cubic feet per minute (SCFM) at 30-psig supply pressure was selected. For the six exhaust valve ports equipped, each injection probe delivered 4.75 SCFM. A routine odor evaluation involved the five operating conditions previously discussed conducted in quadruplicate along with a "blank," in which no exhaust sample was obtained, also presented in quadruplicate to the panel. The twenty-four runs were conducted in random order such that the odor panelists knew only if the run was a transient or a constant speed and were not aware of the order in which the runs were conducted. To facilitate back-to-back measurements with the DEOX system, yet preserve the random order of the conditions, the routine twenty-four runs were doubled to forty-eight runs which covered a period of 2 days, every other run with DEOX operative. This order of presentation was made possible by the simple "on-off" nature of DEOX in that the oxidation air could be added instantly by the opening of the air supply valve.

Table 8 in the text, repeated as Table 6 of Appendix C, is a comparison of the odor evaluations obtained with and without DEOX operative. Listed on Table 8 are each of the five operating conditions and the overall average scores for the diesel composite and the four qualities ("B" - burnt-smoky, "O" - oily, "A" - aromatic-aldehydic, and "P" - pungent). DEOX appeared to have a slight beneficial effect under two of the five conditions investigated. During the 20-mph cruise, DEOX appeared to have a slight effect on the overall intensity as well as a few of the qualities such as "B" and "O." A slightly greater improvement was noted under operating Condition III, the engine idle condition, not only in the "B" - burnt-smoky and "O" - oily qualities, but in the "P" - pungent quality. On the other hand, the use of the manifold oxidation system appeared to be essentially ineffective under the other three operating conditions: the 40-mph cruise, the acceleration after prolonged idle, and the deceleration from 40-mph cruise conditions. One way of analyzing these results may be to note that the DEOX system's effectiveness appeared the greatest under conditions of low engine speed and exhaust flow. At both 20 mph and engine idle, the engine airflow was less than at the other three conditions which were high engine speed and engine exhaust flow conditions.

The comparison shown on Table 8 was based on the odor evaluation data summarized in Tables 7 and 8 of Appendix C for the DEOX system inoperative and operative, respectively. Both Tables 7 and 8 list the panel average for each of the four runs conducted under each of the five odor producing conditions. The results are tabulated by operating condition and indicate the odor characterization for the "D" composite as well as the four qualities which make up the "D" composite. These summaries were prepared from the individual panel responses tabulated in Tables 7A-7E and Tables 8A-8E for the DEOX system inoperative and operative, respectively. For example, Table 7A lists the "D" diesel composite panel responses for each of the twenty runs made (five conditions in quadruplicate) with the DEOX system inoperative during July 12-13. Similarly, Tables 7B-7E list the results for each of the four qualities of "B," "O," "A," and "P," respectively. Tables 8A-8E are similarly constructed and list the individual panel responses for the twenty runs made during July 12-13 with the DEOX system operative.

TABLE 8. COMPARISON OF ODOR EVALUATIONS WITH AND WITHOUT DIESEL EXHAUST MANIFOLD OXIDATION (DEOX*) SYSTEM OPERATIVE

Vehicle: Bus 677.
Date: July 12-13, 1967.

Operating Conditions: See Appendix C.
Fuel: EM-3-F (No. 1 Diesel).

Operating Condition†	DEOX System	"D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	DEOX Inoperative	7.4	2.1	2.0	1.1	1.0
	DEOX Operative	6.5	1.7	1.5	1.0	0.9
Net Change.		-0.9	-0.4	-0.5	-0.1	-0.1
II	DEOX Inoperative	8.3	2.6	2.3	1.3	1.4
	DEOX Operative	8.2	2.6	2.2	0.9	1.5
Net Change.		-0.1	0	-0.1	-0.4	+0.1
III	DEOX Inoperative	7.9	2.3	1.9	1.2	1.7
	DEOX Operative	6.6	1.8	1.5	1.2	0.9
Net Change.		-1.3	-0.5	-0.4	0	-0.8
IV	DEOX Inoperative	8.3	2.5	2.2	1.3	1.7
	DEOX Operative	8.2	2.5	2.1	1.2	1.8
Net Change.		-0.1	0	-0.1	-0.1	+0.1
V	DEOX Inoperative	6.1	1.9	1.3	0.4	1.0
	DEOX Operative	6.6	2.0	1.7	0.5	1.0
Net Change.		+0.5	+0.1	+0.4	+0.1	0

---

*DEOX system involved air injection in the exhaust manifold at the underside of each exhaust valve on left (forward) engine bank (two valves per each of three cylinders).

† I. Constant Speed, 20 mph in drive, 40 hp
II. Constant Speed, 40 mph in drive, 40 hp
III. Idle
IV. Idle-Acceleration
V. Deceleration

The last portion of Appendix C contains the smoke results obtained with the 3/16-in. OD long reach DEOX system shown in Figures 12 and 13. A number of supply pressures and air delivery rates were investigated, listed as follows:

Supply Air Pressure, psig	Total Manifold Oxidation Airflow, SCFM	Oxidation Air per Exhaust Valve
0	0	0
10	13.02	2.17
20	20.3	3.38
30	28.5	4.75
40	34.6	5.77
50	42.6	7.1

This variation in supply pressure and airflow rate resulted in a range of approximately 2 to 7 SCFM of air per exhaust valve and was substantially in excess of the quantity used during the investigation of exhaust dilution conducted during Part I with the Cummins NH-220 engine. Measurements of smoke intensity were made at a variety of maximum power engine/vehicle steady state and transient conditions at the airflow rates listed above. The evaluation conditions, listed in Table 9 of Appendix C, included four steady state conditions of 20 mph with the transmission in the low and in the high drive range, a 30- and 40-mph condition with the vehicle in the drive range. The four constant speed conditions were selected to result not only in a variety of smoke levels but also a wide range of engine speeds and airflows. The procedures employed for these four constant speed maximum power conditions are included as Table 10 of Appendix C.

Listed on Table 11 of Appendix C is the idle-acceleration diesel smoke evaluation procedure which was developed in Part I. During this procedure, a road load condition of 40 hp at 30 mph was preset into the water brake and retained during a full-rack acceleration against both 25, 000 lb of inertia and the road load stored in the dynamometer. The procedure described on Table 11 called for the smoke to be measured at start of engine, during the acceleration after a 1-min idle, and after upshift from the low range to the high range. The average maximum smoke readings were obtained during the acceleration in low range and during the operation of the vehicle after upshift.

TABLE 9. EFFECTIVENESS OF EXHAUST MANIFOLD OXIDATION (DEOX*) ON VISIBLE EXHAUST SMOKE FROM A TWO-CYCLE POWERED BUS

The following comparison is based on results contained in Tables 13 to 18 of Appendix C.

Type of Operation	Vehicle Speed, mph	Average PHS Smoke, %	DEOX Air, Supply Pressures†, psig				
			10	20	30	40	50
A. Constant Speed (Low Range)	20	Without DEOX	8.6	8.6	8.6	8.6	8.6
		With DEOX	9.1	9.2	9.3	9.0	9.5
		Difference	+0.5	+0.6	+0.7	+0.4	+0.9
B. Constant Speed (High Range)	20	Without DEOX	19.3	19.3	19.3	19.3	19.3
		With DEOX	20.0	21.0	23.0	23.5	28.0
		Difference	+0.7	+1.7	+3.7	+4.2	+8.7
C. Constant Speed (High Range)	30	Without DEOX	16.2	16.2	16.2	16.2	16.2
		With DEOX	16.7	17.5	19.0	16.0	17.5
		Difference	+0.5	+1.3	+2.8	-0.2	+1.3
D. Constant Speed (High Range)	40	Without DEOX	8.5	8.5	8.5	8.5	8.5
		With DEOX	8.4	8.5	9.3	9.3	9.3
		Difference	-0.1	0	+0.8	+0.8	+0.8
E. Idle-Acceleration Comparison							
Acceleration after Idle		Without DEOX	7.7	7.7	7.7	7.7	7.7
		With DEOX	9.0	8.3	9.0	7.0	8.0
		Difference	+1.3	+0.6	+1.3	-0.7	+0.3
After Upshift		Without DEOX	14.4	14.4	14.4	14.4	14.4
		With DEOX	15.5	16.3	16.0	13.0	15.0
		Difference	+1.1	+1.9	+1.6	-1.4	+0.6

---

*DEOX system involved air injection in the exhaust manifold at the underside of each exhaust valve on left (forward) engine bank (two valves per each of three cylinders).

†See Tables 14 to 18 of Appendix C for the percent exhaust airflows at each of the operating conditions.

On Table 12 of Appendix C (included as Table 9 of the text) is a comparison of the smoke measurements obtained with DEOX operative and with DEOX inoperative. Shown in Table 9 are the differences in average smoke readings for each of the conditions. Under the high engine speed and corresponding high engine exhaust flow condition (A - constant speed, 20-mph, low transmission range), DEOX made no measurable improvement in the smoke readings. At the same vehicle speed but with the transmission in the high range, the smoke readings increased with DEOX operative compared to DEOX inoperative, as the air supply pressures increased to 50 psig. The differences ranged from approximately 1- to 8.7-percent absorbance increase with DEOX operative relative to DEOX inoperative. As the engine speed/vehicle speed increased to 30 and 40 mph, DEOX had less and less negative effect in that the difference in smoke readings relative to without DEOX operative became less with increasing air supply pressures. Under practically all operating and air supply pressures investigated, the long reach 3/16-in. OD DEOX system appeared to have no positive effect on the reduction of the visible exhaust smoke.

Contained in Tables 13 through 18 of Appendix C are the maximum, minimum, and average smoke readings obtained for the 0-, 10-, 20-, 30-, 40- and 50-psig DEOX air supply pressures, respectively. Indicated on each table are the engine speed, the total DEOX airflow, and the percent of the total exhaust flow of the engine that was added through the six 3/16-in. air injection probes. These tables contain the smoke evaluation for the various DEOX air supply rates investigated and summarized in Table 9 of the text.

C. Summary

The DEOX system of diesel exhaust manifold oxidation appeared to have only a partial effect on the exhaust odor intensity and quality. Although some reductions were measured under the 20-mph cruise and idle conditions, these reductions may not justify DEOX for further consideration. In light of the partial reductions obtained, DEOX can be classified as a limited technical success. From the smoke evaluations made with and without DEOX, no positive reduction in smoke was obtained. The reason for DEOX ineffectiveness relative to the technical success obtained in Part I with a similar DEOX equipped, four-cycle engine may have been the difference in the exhaust gas temperature. The operation of Bus 677, powered by a two-cycle scavenged engine, under municipal bus speeds and loads did not appear conducive to the further oxidation of carbon particles as they exited the combustion chamber. The scavenged air and relatively low speed engine operation may combine to inhibit the beneficial action of the air injected. Contrary to the Part I results, the DEOX air seemed to assist the formation of carbon particles by reducing the combustion gas temperature even further, rather than acting as an oxidizing agent. There may be an optimum combustion gas temperature above which the injection of air is advantageous and below which the injection of air is a detriment.

VI. EFFECT OF JACOBS ENGINE BRAKE ON ODOR AND SMOKE

The Jacobs engine brake, a device to retard vehicles by making the engine act as an air compressor during periods of closed-rack deceleration, has been reported to affect municipal bus exhaust odor and smoke. The Jacobs engine brake, described in Reference 5, helps to slow down the vehicle by opening the exhaust valves at or near top dead center piston position. This permits the air compressed during the compression stroke to be expelled from the combustion chamber instead of expanding within the combustion chamber during the following downward motion of the piston. The release to atmosphere of the kinetic energy stored during compression causes the slowdown. It has been reported that the sudden release of the compressed gases tends to remove soot and carbon buildup in the combustion chamber and exhaust ports as well as keep the exhaust manifolds clean. The improved engine cleanliness in turn improves engine breathing and reduces air box pressures which are thought to have an effect on both vehicle smoke and odor emissions. Because of the number of reports from the field by operators of engines equipped with the Jacobs engine brake systems, a limited evaluation of its effectiveness on the odor and smoke from a two-cycle powered municipal bus under controlled laboratory conditions was justified.

A. Preparations

Fifty buses obtained by the San Antonio Transit System in April 1966 were equipped with Jacobs engine brakes following the successful test of this device on three similar buses powered by E series engines. These fifty newer buses were powered by Detroit Diesel 6V-71, two-cycle, N series engines equipped with type 60N fuel injectors. For purposes of evaluating the effectiveness of the Jacobs brake on the odor and smoke from a two-cycle powered municipal bus, Bus 765 was randomly selected from this group of vehicles.

Certain modifications were required for measurement of smoke and odor. The exhaust pipe was cut off under the bumper to connect the bus exhaust pipe to the central exhaust stack for odor sampling and for connection of a suitable adapter pipe for measurement of smoke. The other modification required with the newer N series powered GM bus was to disconnect the power compensator during open-rack engine operation. This compensator may be seen between the hands of the laboratory technician shown in Figure 15, a photograph of the engine compartment. On these newer GM units equipped with air conditioning, a pneumatically operated device, acting on the governor linkage, compensates for the lack of power that the driver would experience when the air conditioner is in operation. This is done by limiting the amount of power available during periods of time when the air-conditioning system is inoperative. In other words, the engine power output is restricted except when the air-conditioning system is turned on. Rather than operate the air conditioner, which can be a variable load, it was decided that maximum power should always be available. Therefore, the air conditioner was left in the "off" position, the rack compensator removed from the engine governor control, and the unit operated similar to buses powered by E series engines. This permitted back-to-back comparisons at equivalent power levels.

Included as Appendix D are the operating conditions and procedures for odor and smoke measurement employed with Bus 765. Shown on Table 1 of Appendix D are the odor evaluation conditions. The procedures employed for the five odor conditions (conditions I-V) are described in detail in Tables 2 through 5 of Appendix D.

B. Results

On April 13, 1967, Bus 765, with a total mileage of 50, 868 miles and the original fuel injectors still intact, was prepared for test. The results of the initial back-to-back comparison, made on April 13 and 14, 1967, were inconclusive since the same level of smoke and odor emissions was obtained regardless of whether the brake was operative or not. In an attempt to determine conclusively the effectiveness of the Jacobs engine brake, the San Antonio Transit System agreed to operate the vehicle for a period of 3 months with the Jacobs brake disconnected and inoperative. After 3 months of routine operation, such deposits would have a chance to build up, and, if they affected the smoke and odor emissions, these might be noted on a consequent back-to-back evaluation.

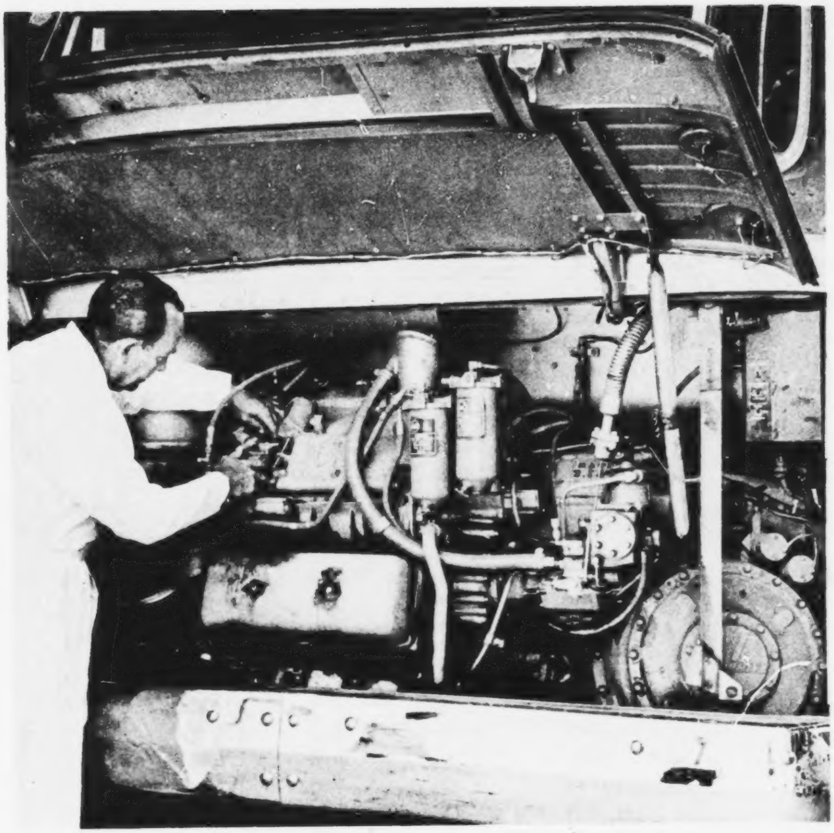


FIGURE 15. ENGINE COMPARTMENT OF GM COACH POWERED BY DETROIT DIESEL 6V-71 ENGINE

The initial and final odor and smoke emissions from Bus 765 were evaluated according to the following schedule:

Test Series	Date	Test Condition	Total Vehicle Miles
Initial	4/13/67	Jacobs brake inoperative	50,868
Initial	4/14/67	Jacobs brake operative	
Final	7/19/67	Jacobs brake inoperative	66,220
Final	7/21/67	Jacobs brake operative	

No engine maintenance, injector replacement, or repair were accomplished during the 3-month period.

An overall summary of the initial and final odor panel responses obtained with and without the Jacobs brake operative is contained in Table 6 of Appendix D and is included in the text as Table 10. Shown on this table are the overall four-run averages for the "D" composite, "B" - burnt-smoky, "O" - oily, "A" - aromatic-aldehydic, and "P" - pungent ratings. These data are listed chronologically and show the initial back-to-back evaluation made on April 13, 1967 (Jacobs brake inoperative) and April 14 (Jacobs brake operative). The final back-to-back evaluation results, conducted on July 19 (Jacobs brake inoperative) and July 21, 1967 (Jacobs brake operative) are listed next. The initial evaluations indicated that, for operating conditions I, II and IV, the "D," "B," and "O" qualities decreased slightly when the Jacobs brake was in operation. During the

TABLE 10. OVERALL SUMMARY OF INITIAL AND FINAL ODOR PANEL RESPONSES WITH AND WITHOUT JACOBS BRAKE OPERATIVE

Vehicle: Bus 765.
Date: April 13-14 &
July 19 & 21, 1967.

Operating Conditions: See Table 1.
Fuel: EM-3-F (No. 1 Diesel).

Operating Condition*	Date Evaluated	"D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	April 13 (off)	6.4	2.1	1.9	1.2	0.6
	April 14 (on)	5.5	1.7	1.5	1.0	0.4
	July 19 (off)	6.0	1.5	1.3	0.8	0.4
	July 21 (on)	5.4	1.7	1.3	0.7	0.4
II	April 13 (off)	6.3	2.0	1.7	0.8	0.6
	April 14 (on)	5.8	1.7	1.5	0.9	0.6
	July 19 (off)	6.5	1.9	1.6	1.2	0.2
	July 21 (on)	5.6	1.7	1.3	0.5	0.4
III	April 13 (off)	5.6	1.9	1.4	1.0	0.6
	April 14 (on)	5.9	1.7	1.5	1.1	1.3
	July 19 (off)	5.9	1.5	1.2	0.9	1.1
	July 21 (on)	6.1	1.9	1.2	0.9	0.8
IV	April 13 (off)	7.4	2.5	2.0	1.4	1.1
	April 14 (on)	6.9	2.2	2.0	1.3	1.0
	July 19 (off)	6.4	1.6	1.5	0.9	0.9
	July 21 (on)	6.8	2.2	2.0	0.9	1.0
V	April 13 (off)	4.1	1.1	1.2	0.6	0.2
	April 14 (on)	5.0	1.2	1.2	0.8	0.3
	July 19 (off)	3.8	1.0	0.9	0.5	0.1
	July 21 (on)	3.7	1.0	1.0	0.4	0.1

---

* I. Constant Speed, 20 mph, 40 hp
II. Constant, 40 mph, 40 hp
III. Idle
IV. Idle-Acceleration
V. Deceleration

idle (condition III) and deceleration (condition V), the reverse was true in that the "D" results were higher with the Jacobs brake in operation relative to the Jacobs brake "off." After 3 months of operation, odor evaluations were obtained, and only during the cruise conditions of 20 and 40 mph did there appear to be a noticeable effect on the exhaust odor. Under the remaining conditions, the Jacobs brake seemed to be about the same or possess slightly higher odor intensity than when the Jacobs brake was inoperative.

In Table 7 of Appendix D, there is a direct comparison of the initial odor evaluations which show that the Jacobs engine brake was not conclusively or consistently effecting an improvement in the exhaust odor. Tables 8 and 9 of Appendix D summarize the routine vehicle odor evaluation conducted on April 13 (Jacobs brake inoperative) and April 14 (Jacobs brake operative), respectively. These two tables summarize the average panel responses for the "D," "B," "O," "A," and "P" qualities for the five odor evaluation conditions. Tables 8A-8E and 9A-9E list the supporting data for Tables 8 and 9, respectively. On Table 10 of Appendix D, comparative data for the final odor evaluation results obtained 3 months after the initial data are listed. During only two of the five operating conditions did noticeable reductions in the exhaust odor quality and intensity occur, namely, constant speed cruises at

20 and 40 mph. In the case of the 20-mph condition, the "B" intensity showed a decrease. During the 40-mph cruise, the "P" quality showed an increase, although the "D, " "B, " "O, " and "A" values decreased. The remainder of the operating conditions investigated showed a slight overall increase in intensity when the brake was operative relative to when the brake was inoperative. The comparison data shown in Table 10 were obtained from the summaries shown on Tables 11 and 12 of Appendix D. These two tables comprise the overall summary for the odor characterization by the SwRI odor panel on July 19, 1967 (Jacobs brake inoperative) and July 21 (Jacobs brake operative). Tables 11A-11E and 12A-12E indicate the panel distribution for the overall diesel composite and each of the four qualities which comprise the composite.

Smoke measurements were obtained using identical conditions established during Part I. The five smoke evaluation conditions and procedures listed in Tables 13 through 15 of Appendix D included operation at constant speed, maximum power, and full-rack acceleration against both inertia and road load. Listed on Table 11 (Table 16 of Appendix D) is the overall summary of the initial and final smoke readings. The constant speed results at 20, 25, 30 and 35 mph are shown first, followed by the idle-acceleration readings at engine start, during low range acceleration, and after upshift. Considering only the initial readings, little difference was measured with the Jacobs engine brake operative or inoperative, regardless of the operating condition. An improvement was noted in the final back-to-back evaluation, especially at 25, 30, and 35 mph. No improvement was noted under any part of the idle-acceleration operation. On Table 17 of Appendix D, a comparison

TABLE 11. OVERALL SUMMARY OF INITIAL AND FINAL SMOKE READINGS WITH AND WITHOUT THE JACOBS BRAKE OPERATIVE

Vehicle: Bus 765.
Date: April 13-14 and
July 19 and 21, 1967.

Operating Conditions: See Appendix D.
Fuel: EM-3-F (No. 1 Diesel).

Constant Speed Results (All at open rack - maximum power)

		Average PHS Smoke Readings, % Absorbance			
		INITIAL		FINAL	
Type of Operation	Vehicle Speed, mph	4/13/67 (Inoperative)	4/14/67 (Operative)	7/19/67 (Inoperative)	4/21/67 (Operative)
A	20	18.0	17.5	15.5	13.3
B	25	11.0	11.0	13.0	9.0
C	30	8.0	8.5	10.5	7.0
D	35	5.7	5.3	8.0	4.5

Idle-Acceleration Results
(40 hp at 30 mph preset and retained)

	Average PHS Smoke Readings, % Absorbance			
	INITIAL		FINAL	
Portion of "E" Idle-Acceleration	4/13/67 (Inoperative)	4/14/67 (Operative)	7/19/67 (Inoperative)	7/21/67 (Operative)
Engine Start	5.3	4.7	9.7	9.8
During Acceleration	5.3	5.7	5.7	7.8
After Upshift	8.3	9.0	7.7	8.3

of the initial smoke readings indicates the net change and average smoke. The final smoke readings, listed on Table 18 of Appendix D, indicate that the Jacobs brake had a slight effect on the visible exhaust plume. This effect seemed greatest at 25-, 30-, and 35-mph maximum power vehicle operation. The magnitude of improvement amounted to approximately 3.5- to 4-percent absorbance reduction from an average reading of 13-percent absorbance at 35 mph, 10.5-percent absorbance at 30 mph, and 8-percent absorbance at 35 mph.

Even though the inoperative Jacobs brake smoke level was low, this level was even less when the Jacobs brake was connected. It should be recalled that the Jacobs engine brake operated only under closed-rack engine deceleration. The small reductions in smoke, therefore, may be attributed to the cleaning effect the brake had on the engine as well as the ability to maintain piston and combustion chamber temperatures which may be conducive to better fuel utilization. One claim that has been made about the Jacobs brake is that it keeps air box pressures from becoming excessive. This may be achieved by a "scouring action" of the released compressed air during the closed-rack deceleration conditions. These hot gases are released as a surge of pressure which tends to remove or prevent exhaust port deposits and buildup. The air box pressures, measured during the final evaluation with the as-received vehicle, did not indicate, however, that a large buildup of exhaust manifold deposits occurred during the 3-month period of operation with the brake disconnected.

C. Summary

In summary of the two back-to-back odor evaluations performed 3 months apart, little beneficial effect on diesel odor was noticed when the Jacobs brake was operative versus when it was disconnected. Only during the final back-to-back evaluation did the Jacobs engine brake appear to have a noticeable, though slight and almost negligible, effect on exhaust smoke. It appears that the Jacobs engine brake is effective as a vehicle retarder but may not hold significant promise for reduction of diesel odor and smoke. The improvements reported in the field may have been largely obtained with the older 6V-71 E series engine equipped with four exhaust valves per cylinder. The four-valve engine, widely used in intercity truck application, was discontinued several years ago in municipal buses due to the tendency of this engine to plug up and breathe poorly. With the advent of the two-valve engine plus the improved N series engine, the exhaust port problem appears to have been reduced. As a result, the Jacobs engine brake cleaning effect appears inconsequential on engine operation and combustion as it influences odor and smoke production.

VII. CATALYTIC MUFFLER EVALUATION

The objective of this portion of the program was to evaluate the performance of several available types and makes of exhaust catalyst devices designed for use with two-cycle diesel powered municipal buses. Three identical fluidized-bed types of catalytic devices, coded "X" ("X"-1, "X"-2, and "X"-3), and one reactor type catalytic device system, coded "Y," were furnished by the manufacturers to the Vehicle Emissions Research Laboratory at the request of the Project Officer. From conversations with the Project Officer, it was agreed that a desirable approach would be to install each muffler in a bus and operate the bus for a month to simulate typical operation. The buses would then be brought into the dynamometer laboratory and the odor and smoke emissions monitored using procedures and conditions established during Part I. The catalyst devices would then be removed, the original mufflers reinstalled, and the bus exhaust reevaluated on the following day. In addition to measurement of pressure drop and intake and outlet exhaust temperatures, selected chemical analysis data were to be obtained.

In conversations with Mr. Ralph Stahman, on April 13, 1967, representing Mr. George Kittredge, Project Officer, it was tentatively agreed to conduct the evaluation of the catalytic muffler devices according to a schedule similar to that shown on Table 12. This schedule was designed to permit maximum statistical information regarding the effectiveness of not only the catalytic muffler relative to the nonequipped unit but also to permit a preliminary evaluation of one catalytic device with another. This schedule optimized the back-to-back evaluation technique (measure diesel odor and smoke with and without catalytic device installed) for the three identical catalytic mufflers, coded "X," and the one catalytic system, coded "Y."

TABLE 12. CATALYTIC MUFFLER EVALUATION SCHEDULE

Time, Days	Bus No. 681 (E Engine)	Bus No. 678 (E Engine)	Bus No. 768 (N Engine)
At 0	Install "X"-1 (June 28, 1967)	Install "X"-2 (July 7, 1967)	Install "X"-3 (July 14, 1967)
At 30	(1) Evaluate "X"-1 (2) Evaluate original muffler (3) Reinstall "X"-1 (Aug. 7-11, 1967)	(1) Evaluate "X"-2 (2) Evaluate original muffler (3) Install "Y" (Aug. 14-18, 1967)	(1) Evaluate "X"-3 (2) Evaluate original muffler (3) Reinstall "X"-3 (Aug. 21-25, 1967)
At 60	(1) Evaluate "X"-1 (2) Evaluate original muffler (3) Install "X"-1 (Sept. 11-15, 1967)	(1) Evaluate "Y" (2) Evaluate original muffler (3) Reinstall "X"-2 (Sept. 4-8, 1967)	(1) Evaluate "X"-3 (2) Evaluate original muffler (3) Reinstall "X"-3 (Sept. 24-29, 1967)
At 90	(1) Evaluate "X"-1 (2) Evaluate original muffler (Oct. 16-20, 1967)	(1) Evaluate "X"-2 (2) Evaluate original muffler (Oct. 9-13, 1967)	(1) Evaluate "X"-3 (2) Evaluate original muffler (Oct. 30-Nov. 3, 1967) (3) Install and evaluate "Y" (4) Evaluate original muffler (Nov. 6-10, 1967).

Three GM Truck and Coach Division Model TDH 4519, forty-five-passenger municipal buses from the San Antonio Transit fleet were selected for this phase. Two of the buses were powered by the Detroit Diesel Division 6V-71, two-cycle, E series engine with two 60S fuel injectors. It was recommended by the PHS statistician that these two buses should be selected as near to the mean as possible of the ten buses involved in the Part I variability study. From a brief statistical review, the odor emissions from Buses 681 and 678 were nearest the mean odor emission level of the ten buses considered. The third bus, Bus 768, was identical to the other two buses but powered by the N version of the Detroit Diesel 6V-71 two-cycle engine equipped with type 60N injectors. This N engine was selected at random from the group of fifty units obtained in April 1966, which were in routine operation by the San Antonio Transit System.

As a result of conversations with Mr. Ralph Stahman, it was decided that in addition to pressure drop across the catalytic mufflers and selected temperatures before and after the catalytic units, carbon monoxide (CO) would be measured. These CO values would be obtained before and after the catalytic device and compared to CO levels obtained with the same bus with the original muffler installed. Because of the expected difficulties in measuring total unburned hydrocarbons from the exhaust and the lack of suitable available instrumentation to permit such measurement, it was not planned to conduct analysis of this type. It was planned, however, to obtain measurements of oxides of nitrogen, acrolein, formaldehyde, total aldehydes, carbon dioxide, and possibly sulfur dioxide. The conditions for many of these wet chemistry determinations were limited to constant speed operation because of the sampling requirements. For further details regarding the basis for selection of the exhaust constituents for measurement, their analytical and sampling procedures, etc., please refer to Section VIII, Exhaust Chemistry and Odor Correlation. Procedures developed for use by Vehicle Emissions Research Laboratory chemists and technicians are included in Appendix E to this report and will be introduced during the discussions of the Code "X"-1 results. Some initial studies with the two-cycle powered bus indicated that the optimum location of the sampling probes for determination of these constituents would be immediately above the odor sampling point in the central exhaust stack as shown in Figure 16. Referring to the top photograph

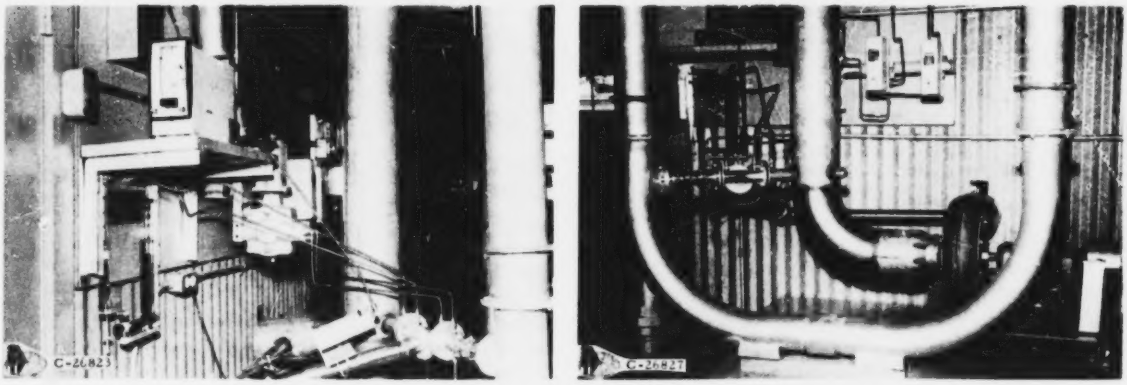


FIGURE 16. DYNAMIC SAMPLING AND DILUTION SYSTEM FOR VEHICLE EXHAUST ODOR DETERMINATION

of Figure 16, the sampling probes were located immediately to the left of the odor sampling tube. The exhaust from the bus would then be sampled for both the wet chemistry analysis and the odor panel at essentially the same place in the high velocity, low residence stream of total vehicle exhaust. Samples were also obtained at this point of CO and CO_2 determination.

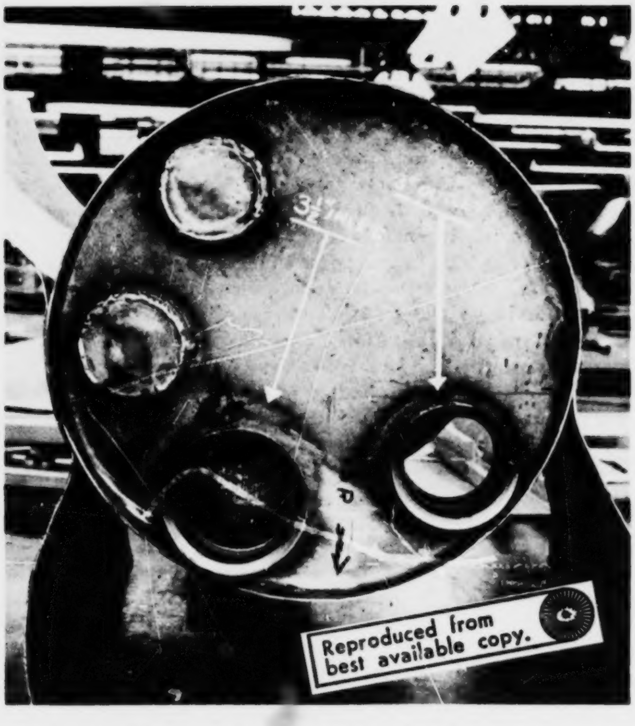
Each of the catalytic muffler performance evaluations required approximately 1 week to conduct. The first day of the week was devoted to obtaining and preparing the vehicle for evaluation. This included necessary connections such as fuel and exhaust piping. The second day was devoted to measurement of various exhaust constituents with the catalytic muffler still installed in the vehicle and in the "as-received" condition. The morning of the second day of this test sequence was used to sample the exhaust under a series of constant speed conditions for CO, CO_2, acrolein, formaldehyde, aliphatic aldehydes, oxides of nitrogen, and sulfur dioxide. The afternoon was utilized to analyze the samples as well as conduct smoke evaluation. The third day was devoted to the evaluation of the odor quality and intensity of exhaust diluted to 100:1 dilution level under realistic vehicle operating conditions. During the afternoon and evening following odor evaluation, the catalytic muffler was removed, the standard stock muffler was installed, and the vehicle reprepared for the following day's evaluation of odor quality and intensity. Then, the smoke inspection with the standard muffler was conducted. On the fifth day of the test period, the exhaust was sampled for various emission constituents similar to those obtained on the second day. During the odor panel measurements on the third and fourth days, muffler inlet and outlet pressures and temperatures were obtained. For the ten evaluations made, the level of effort amounted to 10 laboratory work weeks and resulted in a substantial amount of odor and smoke emissions, and physical temperature and pressure measurement data. These data are contained in Appendix E along with a description of the test and evaluation procedures used. The only fuel utilized throughout this catalytic device evaluation and survey was the commercial number 1 kerosene type diesel fuel. For a complete inspection and analysis of this fuel, designated as EM-3A-F, please refer to Section II of this report. Although the catalytic muffler evaluations involved both Code "X" and "Y" devices concurrently per the schedule of Table 12, the results will be discussed separately, first the three Code "X" units, and then the Code "Y" system.

A. Code "X" Catalytic Muffler Device Evaluation

The Code "X" catalytic muffler device may be described as similar in shape to the stock muffler normally utilized on the municipal buses tested. Normally, the under-the-coach mounted muffler used on the GM Truck and Coach Model TDH 4519 city bus has two 3-in. diameter inlets and one 3-in. outlet. The two 3-in. inlets were required for the two banks of the V6 engine. Figure 17 is an end view of the 16-in. diameter, 23-in. long muffler which has a single 3.5-in. diameter inlet and 3-in. diameter outlet. A suitable "Y" pipe was used to manifold both banks of the 6V-71 engine for single entry into the muffler as shown in Figure 18. This figure shows the retaining screen below which the catalyst bed was mounted and the 3.5-in. inlet pipe above this bed of catalyst. The muffler is shown in an upright position in Figure 18 for illustrative purposes.

The catalyst consists of chemically coated ceramic pellets, approximately 1/4 in. in diameter. The chemical properties and characteristics of the catalyst coating are not known by SwRI and are considered a proprietary item of the catalyst manufacturer. The coated ceramic spheres were contained between stainless steel grids, and the muffler case was fitted with a large diameter pipe plug for adding catalyst and for recharging when necessary. The full charge of the muffler involved 40 lb of catalyst coated ceramic balls. When installed under the bus, the catalytic muffler device was mounted horizontally as shown in Figure 19. Note that the "Y" type connector at the 3.5-in. inlet was located as near the coach floor as possible, and the catalytic material was forced in the lower portion of the device. In other words, the exhaust was forced down through the retaining screen into the catalytic bed and then back through the retaining screen and out the 3-in. outlet. The muffler inlet and outlet openings faced the rear of the bus near the floorboard of the vehicle.

Because of the bulk of information obtained, an attempt has been made to summarize the results in as simple a manner as possible. These summaries have been included in the text of this report and are based on the data and results contained in Appendix E. Although three different buses were employed for the three Code "X" catalytic mufflers and the tests were going on under the



Reproduced from best available copy.

FIGURE 17. END VIEW OF CATALYTIC DEVICE CODE "X"

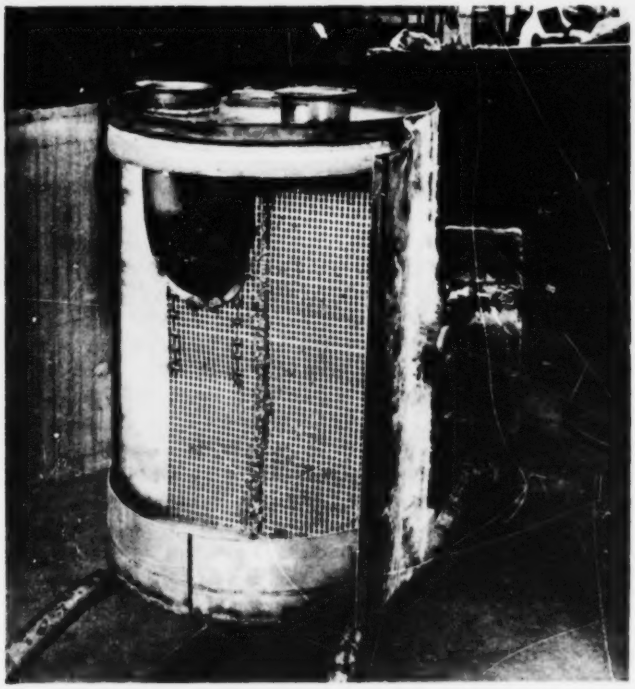
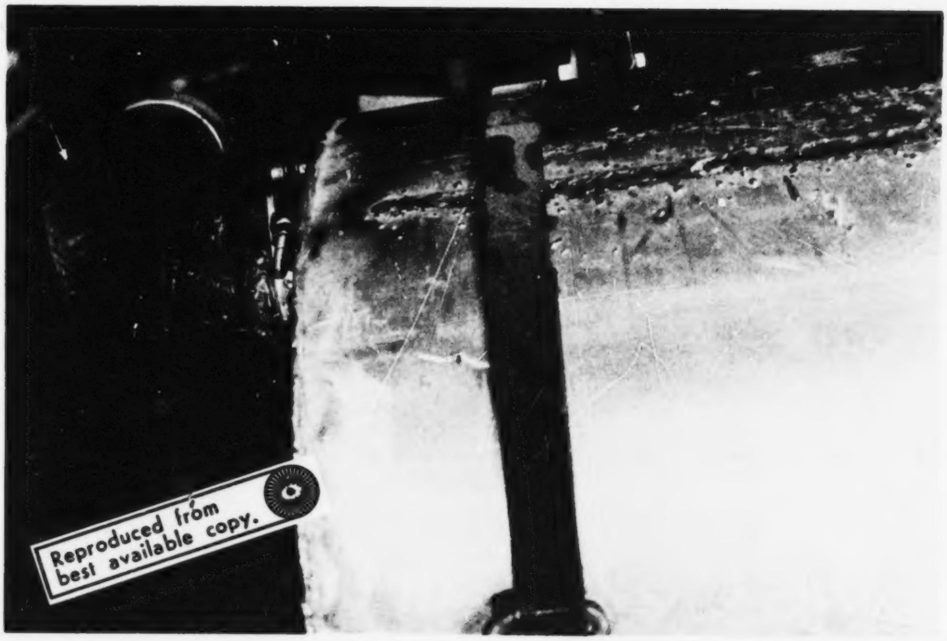


FIGURE 18. CUTAWAY VIEW OF CATALYTIC DEVICE CODE "X"



Reproduced from best available copy.

FIGURE 19. CATALYTIC DEVICE CODE "X" INSTALLED UNDER COACH

schedule shown on Table 12, the results will be reported by device number. This will enable one vehicle and one catalytic muffler to be discussed at a time. For additional details regarding the three vehicles selected for the catalytic muffler evaluations, please see Table 1 in Appendix E. Also listed on this table are engine and driveline specifications, and pertinent maintenance history.

1. Catalytic Device Code "X"-1 Results

Catalytic device Code "X"-1 was installed in Bus 681 and began its initial pretest running period on June 28, 1967. On August 7, after 41 test days and 7777 test miles, it was brought in for the first catalytic muffler evaluation. A detailed and complete log of tests performed with Bus 681, including test days, test mileages, and vehicle/engine maintenance notes, may be found on Table 15 in Appendix E.

Shown on Table 13 of the text is an overall summary of the odor evaluations conducted for this vehicle with the "X"-1 back-to-back with the standard muffler. The operating conditions used are described on Tables 2 through 6 of Appendix E. These odor evaluation conditions were identical to those developed for this type of vehicle during Part I. Listed on Table 13 of the text are these operating conditions and the results obtained at the August, September, and October 1967 test intervals. The test days were computed on the basis of those days the catalytic muffler was in operation and do not include the 5 days the vehicle was out of service for inspection. The average odor panel responses are listed for the overall "D" - diesel composite followed by the four qualities which comprise the "D" composite, namely: the "B" - burnt-smoky, "O" - oily, "A" - aromatic-aldehydic, and "P" - pungent. The results for the standard stock muffler are shown first, followed by the quality/intensity profile for the Code "X"-1 catalytic muffler.

The information in Table 13 indicates the muffler was sometimes successful and sometimes not successful in reducing the panel rating. A number of the differences shown as net change appear to be slight, such as conditions I and II. Figures 20 through 22 show the same information as indicated on Table 13 except they graphically compare each back-to-back evaluation. Recall that the odor panel evaluates first the overall "D" composite on a 1 through 12 scale, the "D"-12 being the strongest and the "D"-1 being the weakest. The concentrations of the "D" standard are arranged so that the perceived odor is a linear relationship to the bottle or standard number. The four

TABLE 13. OVERALL SUMMARY OF ODOR EVALUATIONS CATALYTIC MUFFLER "X"-1 VS STOCK MUFFLER

Vehicle: Bus 681
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	8/10/67	41	7,777	Stock	5.6	1.4	1.6	1.2	0.9
20 mph	8/9/67			"X"-1	7.3	1.8	2.2	1.4	1.3
40 hp				Net Change	+1.7	+0.4	+0.6	+0.2	+0.4
	9/14/67	72	11,042	Stock	4.8	1.5	1.1	1.0	0.6
	9/13/67			"X"-1	5.7	1.8	1.3	1.2	1.0
				Net Change	+0.9	+0.3	+0.2	+0.2	+0.4
	10/18/67	102	15,504	Stock	6.4	2.1	1.7	1.3	1.1
	10/17/67			"X"-1	6.8	2.1	1.8	1.1	1.2
				Net Change	+0.4	0	+0.1	-0.2	+0.1
II	8/10/67	41	7,777	Stock	6.6	1.7	1.7	1.2	1.1
40 mph	8/9/67			"X"-1	6.8	1.7	2.0	1.5	0.9
40 hp				Net Change	+0.2	0	+0.3	+0.3	-0.2
	9/14/67	72	11,042	Stock	5.7	1.9	1.5	0.9	1.0
	9/13/67			"X"-1	5.1	1.6	1.2	1.0	0.7
				Net Change	-0.6	-0.3	-0.3	+0.1	-0.3
	10/18/67	102	15,504	Stock	6.4	2.1	1.9	1.2	1.4
	10/17/67			"X"-1	6.7	2.0	1.6	0.9	1.4
				Net Change	+0.3	-0.1	-0.3	-0.3	0
III	8/10/67	41	7,777	Stock	5.7	1.2	1.6	1.3	1.3
Idle	8/9/67			"X"-1	5.0	1.4	1.3	1.2	0.6
				Net Change	-0.7	+0.2	-0.3	-0.1	-0.7
	9/14/67	72	11,042	Stock	5.5	1.6	1.2	1.1	1.3
	9/13/67			"X"-1	4.2	1.5	1.2	1.2	0.6
				Net Change	-1.3	-0.1	0	+0.1	-0.7
	10/18/67	102	15,504	Stock	7.3	2.4	1.7	1.5	1.9
	10/17/67			"X"-1	6.2	1.9	1.4	1.2	0.9
				Net Change	-1.1	-0.5	-0.3	-0.3	-1.0
IV	8/10/67	41	7,777	Stock	6.3	1.8	1.7	1.2	1.1
Idle-Acceleration	8/9/67			"X"-1	6.4	1.7	1.7	1.4	1.3
				Net Change	+0.1	-0.1	0	+0.2	+0.2
	9/14/67	72	11,042	Stock	6.1	2.0	1.6	1.2	1.1
	9/13/67			"X"-1	4.2	1.7	1.3	0.9	0.8
				Net Change	-1.9	-0.3	-0.3	-0.3	-0.3
	10/18/67	102	15,504	Stock	7.4	2.6	2.0	1.5	1.8
	10/17/67			"X"-1	6.7	2.0	1.5	0.8	1.5
				Net Change	-0.7	-0.6	-0.5	-0.7	-0.3
V	8/10/67	41	7,777	Stock	4.9	1.1	1.3	1.0	0.7
Deceleration	8/9/67			"X"-1	5.3	1.2	1.3	1.4	0.8
				Net Change	+0.4	+0.1	0	+0.4	+0.1
	9/14/67	72	11,042	Stock	3.8	1.2	1.0	0.7	0.3
	9/13/67			"X"-1	3.9	1.2	0.9	0.7	0.2
				Net Change	+0.1	0	-0.1	0	-0.1
	10/18/67	102	15,504	Stock	4.6	1.4	1.1	0.9	0.6
	10/17/67			"X"-1	6.1	1.9	1.3	1.1	0.9
				Net Change	+1.5	+0.5	+0.2	+0.2	+0.3

qualities which make up the "D" composite are also formulated on the basis of a linear perceived odor intensity versus bottle number, but the bottle numbers range from 1 to 4, with 4 being the most intense. For each of the qualities, the gradations within the intensity scale are substantially more coarse than the "D" scale. The quality bottle number 4 corresponds roughly to the bottle number "D"-12 in that a "B"-4 or "O"-4 is the highest or strongest intensity available to the panelist.

In attempting to present the "back-to-back" comparisons in a more revealing manner, the bar charts, Figures 20 through 22 were constructed on a simple addition of "D," "B," "O," "A," and "P" responses. This assumes an arbitrary weighting of the "D" response greater than

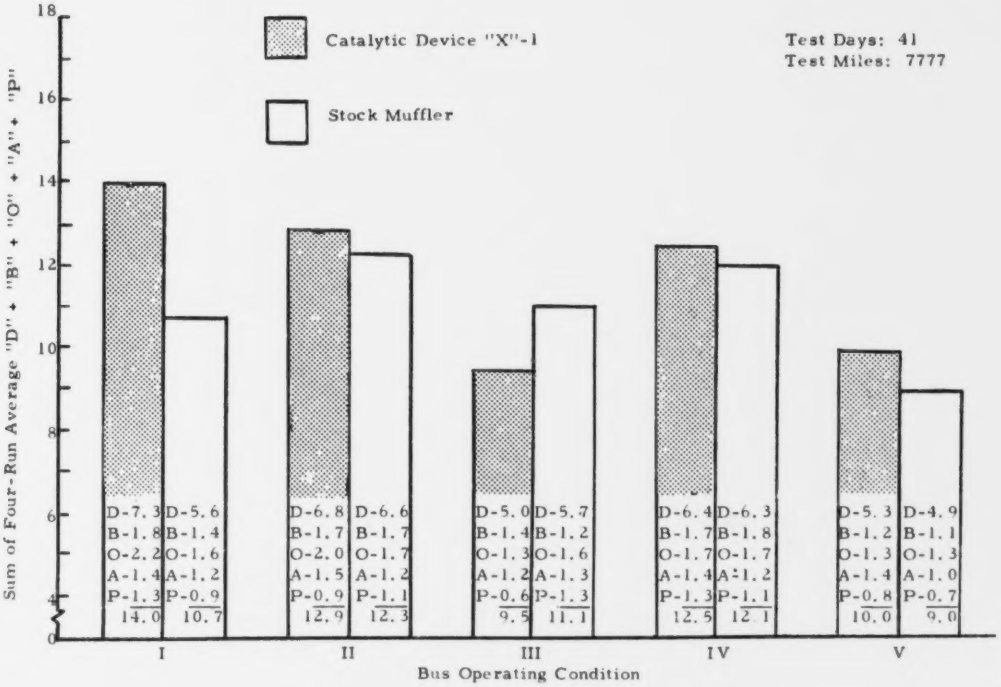


FIGURE 20. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 681, Date: August 9 and 10, 1967)

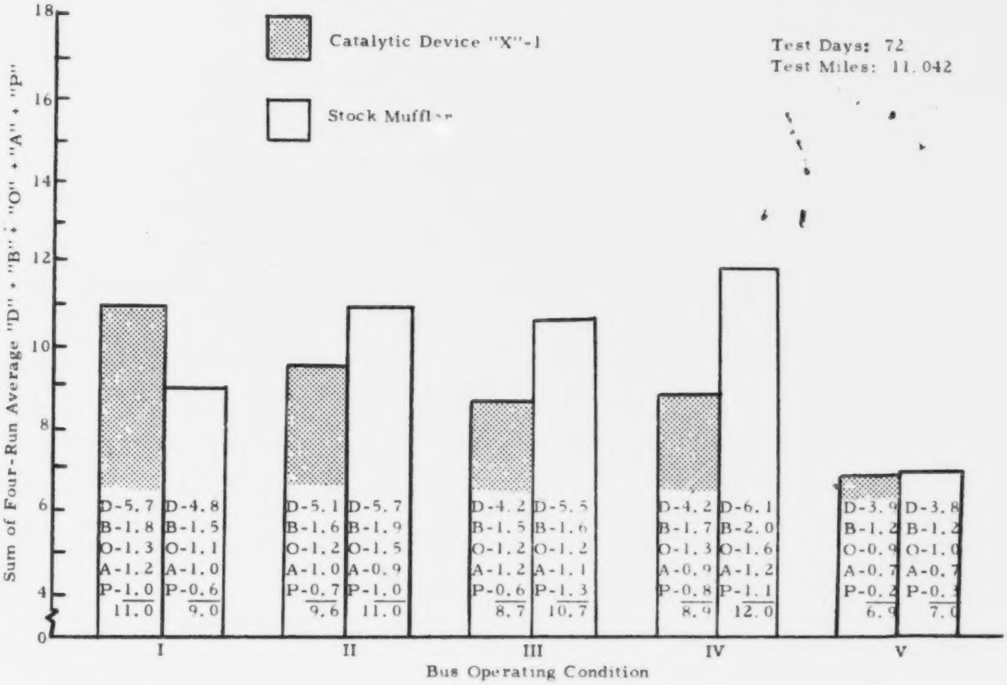


FIGURE 21. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 681, Date: September 13 and 14, 1967)

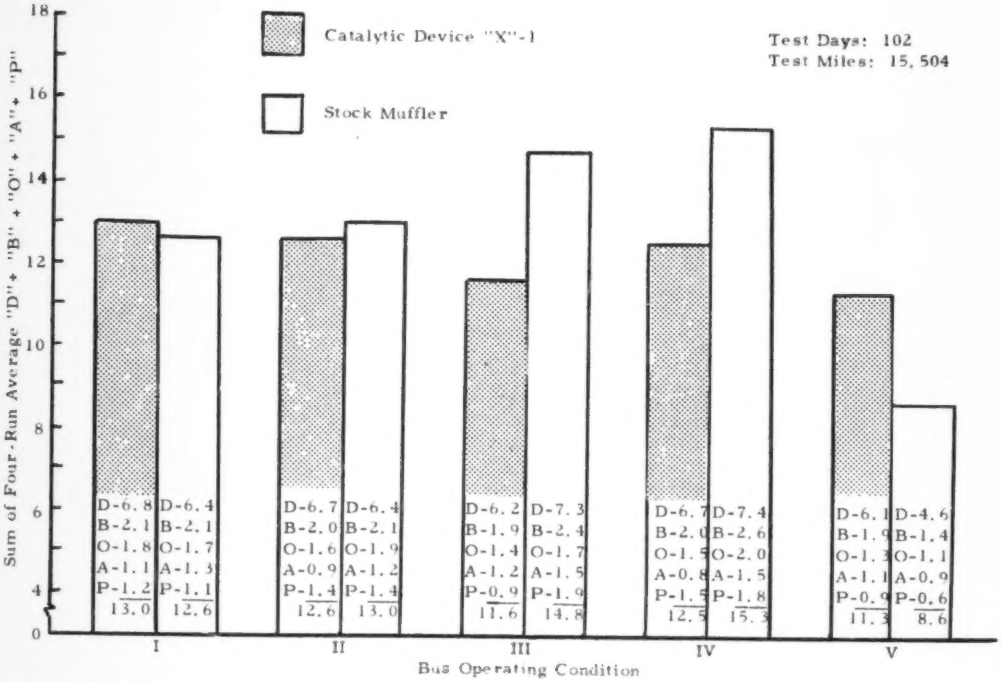


FIGURE 22. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 681, Date: October 17 and 18, 1967)

that given to the individual qualities which make up the "D" response. In conversations with Dr. Amos Turk and others on November 3, 1967, in Cincinnati, this arbitrary assumption seemed reasonable. The arbitrary weighting given the "D" of three times that of the individual qualities may be justified qualitatively since "D" has always been considered the most important and significant indicator of the diesel exhaust odor. The panel always rates for "D" first, and this characteristic seems to have the greatest laboratory-to-laboratory repeatability, as was brought out in the November 3 discussions.

The Figure 20 bar graph, for Bus 681 after 7777 test miles, indicates that only under the idle condition, condition III, did the catalytic muffler appear to have a beneficial effect in reducing diesel exhaust odor. According to Figure 21 for the same vehicle, but after 2 months of operation, the Code "X" catalytic muffler appeared to be effective under operating conditions II, III and IV, the 40-mph cruise, the idle, and idle-acceleration, respectively. The greatest effect appeared under condition IV. From Figure 22 for the same bus and muffler but after 3 months of operation (102 test days and 15, 504 test miles), some reduction in diesel odor during the idle and the acceleration after idle is indicated.

To support the summary of the Code "X"-1 evaluation shown on Table 17 in Appendix E, five additional tables are included, known as Tables 17A-17E. These five tables list in detail the odor panel response distribution for "D, " "B, " "O, " "A, " and "P. " A glance at these tables indicates the panel response distribution as well as the variability and run-to-run variations encountered. Similarly, Table 18 of Appendix E summarizes the twenty runs (five runs in quadruplicate) conducted with the stock muffler on Bus 681. As with the catalytic muffler, five support tables known as Tables 18A-18E list the individual panel responses and indicate response distribution for "D, " "B, " "O, " "A, " and "P, " respectively. The responses from the ten panelists were numerically averaged and grouped by run condition so that the summary average represents the mean of the four runs at that particular operating condition.

The same supporting information is included for the evaluations made at the interim and final evaluation (Tables 24 and 32, Appendix F). Tables 25 and 25A-25E and Tables 26 and 26A-26E provide the supporting information for the interim catalytic and stock muffler evaluations. Tables 33 and 33A-33E and Tables 34 and 34A-34E contain the supporting information for the final evaluations. Considering the response distribution and the variability, the distribution and variability appear similar to that experienced in previous studies.

A statistical evaluation procedure was developed for use in determining if the odor and exhaust emissions results were statistically different for the catalytic relative to the stock muffler. A nonparametric statistical analysis known as the "U" statistic test (Mann-Whitney test) was selected to screen the odor and exhaust emission data. This procedure and an example of the statistical analysis are described on Table 14 of Appendix E. The statistical analysis should be considered as a screening step to indicate, from the bulk of data obtained, those situations, conditions, etc., which appear to be different. Caution must be used in interpreting these statistical differences to keep from placing significance on the data where not warranted. In effect, the "U" statistic does not by itself result in determination of whether the difference is significant or not, and this additional consideration must be given to those data points, conditions, etc., so identified. For purposes of determining whether the catalytic was statistically different from the stock muffler, it was determined that the U_s statistic should range between 0 and 2 where the number of repeat measurements is the same for both mufflers.

The U_s statistical analysis method was applied to the odor evaluations conducted with Bus 681. The results of this analysis, shown in detail on Tables 19, 27 and 35 of Appendix E for the initial, interim and final odor evaluations, are summarized on Table 14 in the text. Only those run conditions and situations in which the "U" statistic was 0 to 2 are listed. More times than not, a statistical difference was not found. The idle-acceleration appeared to have the greatest and most consistent statistical difference. This was followed by the idle condition. Even though a statistical difference was shown for the 20-mph cruise, this difference was not in favor of the catalytic muffler. This interpretation is evident by the average panel responses listed.

It is interesting to consider the bar charts, Figures 20 through 22, in light of the statistical analyses summarized on Table 14. The difference shown in Figure 20 for operating condition I is identified in Table 14 as statistically different. A statistical difference was also found for operating condition I at the interim inspection, Figure 21. Also shown in Figure 21 are the odor reductions measured during condition IV, identified as statistically different according to Table 14. As another example of the correlation of the bar chart data with Table 14 statistics, consider conditions III and IV for the final evaluation, Figure 22. For the relative difference between the stock and catalytic muffler odor responses, a statistical difference did exist. On this same figure, however, under operating condition V, it may be found that the catalytic was not as effective as the stock muffler in reducing odor. This was listed in Table 14 by $U_s = 0$ indicating a statistical difference, yet not a reduction.

The next emission of interest was smoke with and without the catalytic muffler installed. The operating conditions and procedures employed are listed in Tables 7, 8 and 9 of Appendix E. Four constant speed conditions and one transient idle-acceleration condition were investigated and are listed on Table 7 of Appendix E. The constant speed operating conditions of 20, 25, 30 and 35 mph at open-rack, maximum power output are described on Table 8. The idle-acceleration smoke evaluation procedure in which the vehicle was operated at open-rack acceleration with full 25, 000-lb bus inertia simulation is contained in Table 9 of Appendix E.

Shown on Table 15 of the text is an overall summary of the smoke results. The constant speed results were summarized first by operating condition: A--20 mph, B--25 mph, C--30 mph, and D--35 mph, for the initial, interim, and final evaluations. Also listed are the test days and test miles accumulated at the time of each smoke evaluation. Next, the average smoke readings obtained in percent opacity by means of the PHS smokemeter are listed first for the stock and then for "X"-1. Smoke reduction in percent opacity is indicated last. The effect of the catalytic muffler device on vehicle exhaust smoke was negligible and in two instances resulted in slightly increased smoke. On the lower half of Table 15 are the idle-acceleration results which indicate little or no tangible benefit in smoke output with Code "X"-1 versus the standard muffler. The

TABLE 14. ODOR RESPONSE U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "X"-1 VS STOCK MUFFLER

Vehicle: Bus 681
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	8/9/67	41	7,777	"X"-1	7.3	1.8	2.2	1.4	1.3
20 mph	8/10/67			Stock	5.6	1.4	1.6	1.2	0.9
40 hp	U_s Statistic				0	0	1	2	1.5
	9/13/67	72	11,042	"X"-1	5.7	*	1.3	*	1.0
	9/14/67			Stock	4.8		1.1		0.6
	U_s Statistic				1		1.5		0.5
	10/17/67	102	15,504	"X"-1	*	*	*	*	*
	10/18/67			Stock					
	U_s Statistic								
II	8/9/67	41	7,777	"X"-1	*	*	*	1.5	*
40 mph	8/10/67			Stock				1.2	
40 hp	U_s Statistic							0.5	
	9/13/67	72	11,042	"X"-1	*	1.6	1.2	*	*
	9/14/67			Stock		1.9	1.5		
	U_s Statistic					0	0		
	10/17/67	102	15,504	"X"-1	*	*	*	*	*
	10/18/67			Stock					
	U_s Statistic								
III	8/9/67	41	7 777	"X"-1	5.0	*	1.3	*	0.6
Idle	8/10/67			Stock	5.7		1.6		1.3
	U_s Statistic				1.5		2		0.5
	9/13/67	72	11,042	"X"-1	*	*	*	*	0.6
	9/14/67			Stock					1.3
	U_s Statistic								0.5
	10/17/67	102	15,504	"X"-1	6.2	1.9	*	*	0.9
	10/18/67			Stock	7.3	2.4			1.9
	U_s Statistic				1	2			0
IV	8/9/67	41	7,777	"X"-1	*	*	*	*	*
Idle-Acceleration	8/10/67			Stock					
	U_s Statistic								
	9/13/67	72	11,042	"X"-1	4.2	1.7	1.3	*	0.8
	9/14/67			Stock	6.1	2.0	1.6		1.1
	U_s Statistic				0	2	0.5		2
	10/17/67	102	15,504	"X"-1	6.7	2.0	*	0.8	*
	10/18/67			Stock	7.4	2.6		1.5	
	U_s Statistic				1.5	0		0	
V	8/9/67	41	7,777	"X"-1	*	*	*	1.4	*
Deceleration	8/10/67			Stock				1.0	
	U_s Statistic							0.5	
	9/13/67	72	11,042	"X"-1	*	*	*	*	*
	9/14/67			Stock					
	U_s Statistic								
	10/17/67	102	15,504	"X"-1	6.1	1.9	*	1.4	1.5
	10/18/67			Stock	4.6	1.4		1.0	1.8
	U_s Statistic				0	0		0.5	0

*U_s statistic greater than 2, no statistical difference apparent.

smoke data shown on Table 15 summarize the smoke readings contained on Tables 20, 28, and 36 of Appendix E for the initial, interim, and final evaluations. Please refer to these three tables for additional smoke data, as well as vehicle power readings.

Summarized on Table 16 of the text are the average "as-measured" exhaust emissions, and muffler pressure and temperature measurements obtained for "X"-1 versus the stock muffler for Bus 681. This table is constructed in two portions: the top portion summarizing the average "as-measured" exhaust emissions, and the bottom portion summarizing the average muffler pressure and temperature measurements. Using direct sampling of the diesel exhaust from the same point at which the samples were obtained for dilution and presentation to the odor panel, selected chemical constituents in the raw diesel exhaust were collected and analyzed. Before

TABLE 15. OVERALL SUMMARY OF SMOKE EVALUATIONS CATALYTIC MUFFLER "X"-1 VS STOCK MUFFLER

Vehicle: Bus 681
Fuel: EM-3A-F

Operating Conditions: See Tables 7 through 9 in Appendix E

Dates Evaluated: See below.

Constant Speed (All open rack - maximum power output):

Operating Conditions	Vehicle Speed, mph	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity Stock	"X"-1	Smoke Reduction, Percent Opacity
A	20	8/9,10/67	41	7,777	11.7	9.3	2.4
		9/13,14/67	72	11,042	10.3	10.3	0
		10/16,18/67	102	15,504	9.7	7.5	2.2
B	25	8/9,10/67	41	7,777	8.8	8.8	0
		9/13,14/67	72	11,042	8.5	7.3	1.2
		10/16,18/67	102	15,504	6.0	6.0	0
C	30	8/9,10/67	41	7,777	6.8	7.7	(0.9)*
		9/13,14/67	72	11,042	7.3	6.3	1.0
		10/16,18/67	102	15,504	6.0	5.2	0.8
D	35	8/9,10/67	41	7,777	5.5	7.2	(1.7)
		9/13,14/67	72	11,042	6.5	5.3	1.2
		10/16,18/67	102	15,504	5.5	4.6	0.9

Idle-Acceleration (40 hp at 30 mph preset and retained):

Portion of "E" Idle-Acceleration	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity Stock	"X"-1	Smoke Reduction, Percent Opacity
Engine Start	8/9,10/67	41	7,777	8.0	5.0	3.0
	9/13,14/67	72	11,042	8.7	9.0	(0.3)
	10/16,18,67	102	15,504	8.0	7.0	1.0
During Acceleration	8/9,10/67	41	7,777	5.0	8.2	(3.2)
	9/13,14/67	72	11,042	4.2	4.7	(0.5)
	10/16,18/67	102	15,504	4.7	3.7	1.0
After Upshift	8/9,10/67	41	7,777	6.2	9.7	(3.5)
	9/13,14/67	72	11,042	5.7	6.0	(0.3)
	10/16,18/67	102	15,504	4.6	4.2	0.4

---

*( ) indicates increase in smoke with catalytic muffler installed.

discussing the results shown on Table 16, it may be helpful to review the basis for measuring the constituents listed and describe the sampling and analysis methods employed. CO and CO_2 were measured to provide an indication of the repeatability of operation and stability of the vehicle and engine during the 3-min sampling period employed. The main reason for measuring CO was to obtain base line data and, in conjunction with CO_2, to provide a simple basis for adjusting "as-measured" emissions values. CO and CO_2 data may be used to correct for the variations and sometimes large amount of excess air handled by the diesel engine and found in the exhaust. The adjustments, therefore, may be considered as a normalizing factor which permits a more direct comparison of the various exhaust emissions to those obtained from other types of power plants such as a four-cycle type diesel engine, other two-cycle type diesel engines and, when necessary, certain emissions from spark-ignited gasoline powered engines. The measurement of acrolein, aliphatic aldehydes, formaldehyde and oxides of nitrogen appeared justified as a result of the Scott-Katti correlation program, Reference 6. Sulfur dioxide was included to obtain additional information regarding these products of combustion.

TABLE 16. SUMMARY OF AVERAGE "AS-MEASURED" EXHAUST EMISSIONS AND MUFFLER PRESSURE AND TEMPERATURE MEASUREMENTS CATALYTIC MUFFLER CODE "X"-1 VS STOCK MUFFLER

Vehicle: Bus 681
Fuel: EM-3A-F

Operating Conditions:
Exhaust Emissions: See Table 10
Muffler Pressure and Temperature: See Tables 11 & 12

Average "As-Measured" Exhaust Emissions

Operating Conditions	Test Date	Test Days	Test Miles	CO, ppm		CO_2, percent		Acrolein, ppm		Aliphatic Aldehydes, ppm*		Formaldehyde, ppm		NO_x, ppm NO_2		SO_2, ppm		Adjusting Factor†	
				Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1
I	8/8, 11/67	41	7,777	540	600	5.25	5.45	2.71	2.73	15.4	33.2	11.5	17.0	675	647	1.01	1.00	2.83	2.73
20 mph	9/12, 13/67	72	11,042	395	490	5.1	5.35	3.87	4.82	24.8	29.5	11.8	21.1	566	582	0.34	1.10	2.92	2.78
40 hp	10/16, 19/67	102	15,504	270	380	4.4	4.5	1.87	2.24	20.4	19.8	6.75	7.05	716	820	0.30	0.29	3.39	3.31
II	8/8, 11/67	41	7,777	180	200	4.0	4.1	2.22	2.50	14.4	27.1	11.8	16.3	404	416	1.44	1.38	3.73	3.64
40 mph	9/12, 15/67	72	11,042	140	165	3.95	4.2	2.46	2.38	21.8	28.7	9.9	16.2	367	372	0.94	0.52	3.78	3.56
40 hp	10/16, 19/67	102	15,504	150	155	3.4	3.5	2.08	1.44	20.9	18.1	6.9	7.05	482	506	0.29	0.30	4.40	4.27
III	8/8, 11/67	41	7,777	275	290	1.1	1.1	4.15	1.96	20.3	28.4	18.5	18.9	158	176	0.25	0.34	13.3	13.3
Idle	9/12, 15/67	72	11,042	205	220	1.1	1.2	4.05	2.28	29.3	29.3	16.0	16.4	160	154	0.29	0.35	13.45	13.35
	10/16, 19/67	102	15,504	220	210	1.1	1.1	2.32	1.72	25.0	22.1	12.4	11.6	147	164	0.15	0.16	13.45	13.45

Average Muffler Pressure and Temperature Measurements

				Muffler Pressure, in. Hg						Muffler Temperature, °F						Air Box Pressure, in. Hg	
				Inlet		Outlet		Differential		Inlet		Outlet		Differential			
				Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1	Stock	"X"-1
I	8/9, 10/67	41	7,777	0.9	0.9	0.40	0.30	0.5	0.6	504	473	402	353	102	120	1.4	1.6
20 mph	9/13, 14/67	72	11,042	1.0	1.0	0.40	0.35	0.6	0.65	531	536	472	432	59	104	1.55	1.55
40 hp	10/17, 18/67	102	15,504	0.9	0.9	0.40	0.3	0.5	0.58	504	489	402	352	102	137	1.4	1.6
II	8/9, 10/67	41	7,777	3.2	3.0	1.4	1.0	1.8	1.9	546	503	473	462	73	41	6.5	6.4
40 mph	9/13, 14/67	72	11,042	3.45	3.25	1.35	1.3	2.05	2.05	593	577	546	544	47	33	7.8	7.7
40 hp	10/17, 18/67	102	15,504	3.2	2.9	1.4	1.0	1.8	1.9	546	503	457	462	89	41	6.5	6.4
III	8/9, 10/67	41	7,777	0.25	0.25	0.10	0.10	0.10	0.15	271	265	309	360	38	95	1.3	1.2
Idle	9/13, 14/67	72	11,042	0.25	0.25	0.10	0.05	0.15	0.20	314	294	350	413	36	119	0.75	0.70
	10/17, 18/67	102	15,504	0.25	0.25	0.10	0.10	0.10	0.15	271	269	309	373	38	104	1.3	1.2
IIIa	8/9, 10/67	41	7,777	1.8	1.7	0.8	0.6	1.0	1.1	495	463	403	394	92	69	3.1	3.2
30 mph	9/13, 14/67	72	11,042	1.95	1.9	0.75	0.7	1.15	1.1	535	546	494	472	41	74	4.05	3.7
40 hp	10/17, 18/67	102	15,504	1.8	1.7	0.8	0.6	1.0	1.2	495	464	403	394	92	70	3.2	3.1

---

*Total as ppm formaldehyde.

†Adjusting factor is computed by dividing 15 by the percent (CO and CO_2) in the exhaust using "as-measured" average CO and CO_2 measurements.

The vehicle conditions, sample procedure, and analytical methods employed for measurement of exhaust constituents may be found on Table 10 of Appendix E. Due to the direct stream sampling procedures employed in which a 3-min sample at a 1-liter per min rate of exhaust was absorbed in various wet chemistry type glassware, the three constant speed conditions normally employed in the measurement of odor were selected. These three constant speed conditions were condition I, 20-mph cruise, condition II, a 40-mph cruise, and condition III, an idle after sustained operation at 30 mph. The procedure followed very closely the methods used for odor analysis by the human panel except the constant condition was held for a period of 3 min instead of the approximately 50 to 70 sec necessary for the human odor panel. Instead of operating these conditions in random order as was the case with the panel, a sequence of conditions I, II and then III was employed, and this sequence was repeated three times to result in three operating conditions conducted in quadruplicate. Also listed on Table 10 of Appendix E are the analytical procedures used for each constituent measured. Carbon monoxide and carbon dioxide were measured by Beckman Model 315 nondispersive infrared (NDIR) analyzers suitably modified for the low-range CO involved. The CO NDIR was equipped with a 5.25-in. sample cell, 5-in. filter cell and 0.25-in. filter cap with a 10.5-in. reference cell to measure 0- to 2000-ppm CO span. Oxides of nitrogen were measured using the modified Saltzmann syringe method in which the NO is converted to NO_2 and reported as ppm NO_2. To determine sulfur dioxide, the West and Gaeke method was utilized. The 4-hexylresorcinol method was employed to determine acrolein. The MBTH method was used for total aliphatic aldehydes, and the chromatropic acid method was employed for measurement of formaldehyde. Basic references are listed for each procedure or method employed.

Returning to the measurements summarized on Table 16 of the text, the effect of the catalytic muffler on CO and CO_2 production was negligible. In some instances, the CO production appeared higher with the "X"-1 muffler, and this was particularly evident during the 20-mph cruise. Acrolein results showed little important changes except at the idle condition in which a consistent reduction from about 4 to 2 ppm, as evident at the initial and interim inspections at the end of 7777 test miles (41 test days) and 11, 042 test miles (72 test days), respectively. At the final inspection (102 test days or 15,504 test miles), the reduction was still apparent but not as large. Other operating conditions indicate little tangible reduction in acrolein and, on some occasions, a slight but measurable increase in acrolein.

Total aliphatic aldehydes and formaldehyde, the most elementary aldehyde, showed more important changes with "X"-1 compared to the stock muffler. The aldehydes and formaldehyde data may be discussed together since the changes appear to correspond by operating condition and test date. For example, for the 20-mph cruise, the initial results indicated there were more aldehydes and formaldehyde in the exhaust when the "X"-1 muffler was operated than when the standard unit was operated. This effect was also noticed at the interim inspection. The increase in aldehyde concentration, however, was not quite as large as that found during the initial set of tests. The formaldehyde increase was somewhat larger than the initial measurement. The final set of readings indicated that the aldehydes and formaldehyde concentrations were about the same from both the stock and the "X"-1 muffler. Considering the 40-mph cruise, the results of the initial inspection again indicated more aldehydes and formaldehyde in the exhaust when the vehicle was operated with the "X"-1 muffler than with the standard unit. This trend was also found at the interim inspection after 72 test days. As with the 20-mph cruise condition, the final test inspection indicated approximately equal aldehydes and formaldehyde concentration in the exhaust as per Table 16. Considering the idle condition, the total aldehydes from the vehicle operated with "X"-1 were greater than those obtained with the stock muffler for the initial inspection. The formaldehyde concentrations were almost identical. The concentration of total aldehydes and formaldehyde appeared to be about the same with the stock or with the "X"-1 muffler during the interim and final vehicle inspections made. A slight reduction in total aldehydes from the "X"-1 muffler was found at the final inspection.

Oxides of nitrogen, which are reported as ppm NO_2, are listed next on Table 16. Reviewing the average "as-measured" results for "X"-1 versus the stock muffler, there were essentially no gross differences in this emission at any of the operating conditions investigated. The only change in NO_x which appeared to have a consistent pattern was the higher readings obtained with "X"-1 relative to the stock muffler as noted during the final inspection. This increase was most pronounced under the 20- and 40-mph cruises. The sulfur dioxide "as-measured" results indicate no gross change in the oxides of sulfur in the vehicle exhaust. Some slight disagreement is apparent from the results listed at 20 and 40 mph during the interim evaluation. The 20-mph data indicate an increase in SO_2 with the "X"-1 muffler, yet a decrease is indicated with this same muffler when the vehicle was operated at 40 mph.

The final column of Table 16 lists adjusting factors to normalize the average "as-measured" exhaust emissions for the effect of diluent air in the engine exhaust. The characteristic of a diesel engine is to run overall air rich under all operating conditions. The amount of excess air necessary for combustion represents a dilution of the combustion products which is a variable depending on operating speed and load. For example, at engine idle conditions (no load), the amount of excess air is substantially greater than that handled during periods of fully loaded, high-power, open-rack operation. Multiplication of the "as-measured" exhaust emissions by the adjusting factor will place the "as-measured" emissions on an equal basis. An approximate adjusting factor was computed by dividing 15 by the total of the percent CO and CO_2 as measured in the exhaust. This procedure appears justified and has been used by a number of investigators for normalizing "as-measured" data in diesel exhaust. For a brief treatment of this technique, please see Reference 7. Applying the adjusting factor to the "as-measured" data tends to multiply the idle emissions by about 13 to 13.5 and the emissions obtained under 20- and 40-mph cruise by approximately 3 and 4, respectively, for the exhaust from Bus 681.

The measured exhaust emissions obtained at the initial, interim, and final vehicle inspections for Bus 681 are contained in Appendix E, Tables 21, 29 and 37, respectively. From these tables, the degree of variability in results and spread in the data can be seen. In general, all of the measurement systems and techniques appeared to give reasonably reliable data. The range of values in most cases were found within expected experimental error. The CO and CO_2 values, obtained by NDIR may be considered quite reliable. The measurement of oxides of nitrogen by means of the Saltzman syringe technique had better than expected results as indicated by the range of values listed. Duplicate syringe samples were obtained in succession during each run so that for the twelve runs (three conditions in quadruplicate) a total of twenty-four syringe samples were taken.

Sulfur dioxide values appear to have the greatest amount of variability, and the results obtained by sampling and analytical techniques should be so interpreted. The reason for this variability has not been completely determined.

A statistical analysis was conducted of the "as-measured" exhaust emissions to screen and identify those instances in which the "X"-1 muffler appeared to represent a statistical difference over the emissions measured with the stock muffler. The nonparametric Mann-Whitney U_s analysis was applied to the "as-measured" exhaust emissions data. Two qualifying remarks should be made regarding the application of this method to the exhaust emissions data. First, in cases where the two sets of data were not equal, such that only three instead of four repeat measurements were obtained, the U_s statistic was felt important when it was equal to 0 to 1.5. The other comment is that results of the U test must be viewed with some caution and insight as to the method of measurement, its repeatability and range of variability. For example, the U test will show a statistical difference for a set of readings of 150-, 150-, 151- and 149-ppm CO and a set of readings of 155-, 156-, 154- and 154-ppm CO. When these two sets of readings are considered from a practical standpoint, in which the limitations of the NDIR and other equipment, sampling, etc., are involved, it may be seen that these two sets of readings are really not different at all but are essentially the same. Therefore, it is with this precaution of using common sense and engineering judgment that the statistical results obtained from the U test must be viewed.

Summarized on Table 17 are the results of the statistical analysis of differences of the exhaust emission data. Only when the statistical analysis indicated a difference were the values brought forward from the supporting tables in Appendix E and indicated. The 20-mph operating condition (initial evaluation) indicated that total aldehyde concentration in the exhaust from the "X"-1 muffler were statistically different from the stock. Considering the average "as-measured" data shown on Table 17, the "X"-1 concentration was higher, approximately twice as great as that measured when the stock muffler was installed. During the interim evaluation for the 20-mph cruise, there appeared to be a statistical difference between formaldehyde, oxides of nitrogen, and sulfur

TABLE 17. EXHAUST EMISSIONS U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "X"-1 VS STOCK MUFFLER

Vehicle: Bus 681
Fuel: EM-3A-F

Operating Conditions: See Tables 10 – 14 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average "As-Measured" Exhaust Emissions						
					CO, ppm	CO_2 percent	Acrolein, ppm	Aldehydes, ppm Form.	Formaldehyde, ppm	NO_x, ppm	SO_2, ppm
I 20 mph 40 hp	8/8/67	41	7,777	"X"-1	*	*	*	33.2	*	*	*
	8/11/67			Stock				15.4			
	U_s Statistic							0			
	9/12/67	72	11,042	"X"-1	*	*	*	*	21.1	582	1.10
	9/15/67			Stock					11.8	566	0.34
	U_s Statistic								0	0	0
	10/16/67	102	15,504	"X"-1	300	*	7.4	*	*	820	*
	10/18/67			Stock	270		6.35			716	
	U_s Statistic				1		2			0	
II 40 mph 40 hp	8/8/67	41	7,777	"X"-1	200	*	*	27.1	16.3	*	*
	8/11/67			Stock	180			14.4	11.8		
	U_s Statistic				0			0	0		
	9/12/67	72	11,042	"X"-1	165	*	*	28.7	16.2	*	*
	9/15/67			Stock	140			21.8	9.9		
	U_s Statistic				0			2	0		
	10/16/67	102	15,504	"X"-1	*	*	1.44	18.1	*	506	*
	10/18/67			Stock			2.08	20.9		462	
	U_s Statistic						1	2		0.5	
III Idle	8/8/67	41	7,777	"X"-1	*	*	1.96	28.4	*	*	0.34
	8/11/67			Stock			4.15	20.3			0.25
	U_s Statistic						0	0			0
	9/12/67	72	11,042	"X"-1	*	*	*	*	*	*	*
	9/15/67			Stock							
	U_s Statistic										
	10/16/67	102	15,504	"X"-1	*	*	1.72	22.1	*	164	*
	10/18/67			Stock			2.32	25.0		147	
	U_s Statistic						0	0		2	

---

*U_s statistic greater than 2, no statistical difference apparent.

dioxide, and, in all cases, the catalytic was higher than the stock muffler. The NO_x values of 582- and 566-ppm NO_2 are adjudged to be close enough to preclude there being a significant difference. The SO_2 statistical difference shown is questionable on the basis previously stated. During the final inspection, the U test indicated a difference in CO, acrolein and NO_x. The differences found, however, were not gross differences. For example, the difference of 30-ppm carbon monoxide is not adjudged to be a significant difference between the stock and the "X"-1 muffler. Neither is the 1-ppm difference in acrolein results. The difference of approximately 100-ppm NO_2 is interesting in that the NO_x from the catalytic muffler was higher than that from the stock muffler.

Considering the results on Table 17 for the 40-mph cruise, differences were indicated for CO--initial and interim; acrolein--final, aldehydes--initial, interim, final; formaldehyde--initial and interim; and NO_x--final. The differences in carbon monoxide, though statistically different, were not felt significantly different. The change in acrolein downward with the catalytic muffler relative to the stock muffler (final inspection) was encouraging but not considered a gross change. The differences in aldehydes found during the initial and interim inspections at 40 mph were in favor of the stock muffler. The difference shown statistically during the final evaluation was not considered significant. The formaldehyde values obtained during the initial and interim inspections showed a measurable increase in formaldehyde when the catalytic muffler was operated relative to the stock muffler. The statistical difference shown for oxides of nitrogen (final evaluation) was not considered significant.

The idle condition data indicate a difference existed only during the initial and final inspections. Although acrolein appeared to be cut in half with the catalytic muffler, aldehydes appeared to increase, relative to the stock muffler, as measured during the initial inspection. The slight difference in sulfur dioxide is not adjudged significant in light of measurement difficulties. The final evaluation indicated a statistical difference in the downward direction for both acrolein and aldehydes, and in the upward direction for oxides of nitrogen for "X"-1 relative to the stock muffler. Although some significance may be given to the difference in catalytic and stock acrolein emissions, the difference of 3 ppm in aldehydes does not appear significant nor does the difference of 17-ppm NO_2 warrant special consideration. In summary of the discussion of Table 17, some of the emissions are indicated as statistically different for the "X"-1 muffler relative to the stock muffler. When analyzed from an engineering standpoint and the differences considered in light of the measurement technique employed, only a few data points seem to have actual significance. Contained in Tables 22, 30 and 38 of Appendix E are the statistical analyses for the initial, interim, and final inspections. Please refer to these three tables for additional details regarding the statistical analyses summarized on Table 17 in the text.

The final set of measurements obtained during each inspection was the inlet and outlet muffler temperatures and pressures and engine air box pressures. The muffler temperatures and pressures were measured simultaneously with the odor evaluations and included the two constant speed cruises at 20 and 40 mph, conditions I and II. These procedures are described on Table 11 of Appendix E. Measurements were also obtained during the idle, condition III, and during the subsequent cruise at 30 mph and 40 hp, designated condition IIIa. For a description of the procedure used in obtaining the muffler and air box data under conditions III and IIIa, please refer to Table 12 of Appendix E. These procedures involved measuring the exhaust gas static pressure at the inlet and outlet with a simple U-tube mercury manometer. Then, the manometer was connected across the muffler and the differential pressure measured. Muffler temperatures were obtained at the inlet and outlet using chromel-alumel type K thermocouples and a millivolt potentiometer. The thermocouple was located midway in the gas stream at the same position as the pressure taps. The differential temperature was computed by subtracting the outlet temperature from the inlet temperature. Air box pressure was measured as specified in the manufacturer's shop manual using an open U-tube mercury manometer.

Shown on the lower portion of Table 16 in the text is an overall summary of the average muffler pressure and temperature, as well as air box pressure measurements. The results are listed by operating condition chronologically so that the initial, interim and final inspection results are given first for the 20-mph and then for the 40-mph operating condition, followed by the idle and the 30-mph cruise which precedes the idle. Considering all the muffler inlet and outlet pressure measurements, the inlet muffler pressures were not excessive when compared to the maximum backpressure allowable with this type of engine as shown on the following page.

	Engine Speed, rpm		
	1200	1800	2100
Exhaust Backpressure--Inches Mercury (Max.)*			
Full Load	1.5	3.3	4.0
No Load	1.0	2.1	2.6

Considering the pressure drop across the muffler unit, there appears to be little difference in pressure drop tendencies with either the standard or the "X"-1 device. If anything, "X"-1 had a very slight increase in pressure drop relative to that with the stock muffler.

The inlet temperatures were always higher than the outlet temperatures, resulting in a temperature drop or decrease across the stock muffler. A temperature drop was evident at the 20-, 40-, and 30-mph cruises. This was not the case, however, during the idle condition which followed a 30-mph cruise. The muffler outlet temperatures were actually higher than the muffler inlet temperatures, resulting in a temperature rise across the muffler rather than a drop. This temperature increase under the idle condition may be explained when it is recalled that there were 40 lb of 1/4-in. diameter pellets within the catalytic muffler. In effect, the catalytic muffler acted similar to a pebble bed heater in which the 30-mph, 40-hp cruise exhaust gases heated the pebbles up to approximately 450° to 500°F and then imparted the heat stored by this mass of material to the relatively cool 275° to 300°F incoming exhaust during the idle condition. For the approximate 1-min required during the idle odor evaluation, the "X" catalytic muffler increased the exit temperature of the exhaust gas.

According to the vehicle manufacturer, the following air box pressures are specified.

	Engine Speed, rpm		
	1200	1800	2100
Air Box Pressure--Inches Mercury*			
Minimum at Zero Exhaust Back-pressure (2 Valve)	1.7	4.4	6.2
Minimum at Maximum Exhaust Backpressure ("N" Series)	3.3	6.4	8.2

These air box pressures are based on operating the engine under no load with the transmission in neutral. Comparing the values summarized in Table 16 of the text with the specified levels, air box pressures measured for both stock and "X"-1 mufflers were within specifications. Additionally, the air box pressures did not appear to be greatly affected by the presence of the catalytic muffler. Apparently the modified piping in front of the muffler did not seriously change the breathing characteristic of this two-cycle engine as the pressure drop across the catalytic muffler was only slightly higher than that measured with the stock muffler.

Contained on Tables 23, 31 and 39 in Appendix E are summaries of the initial, interim, and final pressure and temperature measurements. The summarized data on the lower portion of Table 16 are based on averages of the data shown on these three tables in Appendix E. Also shown on these three tables are the air box pressures obtained under no load engine operation with the transmission in neutral. The procedure employed to determine these pressures is described on Table 13 of Appendix E. Comparing the air box pressure measurements under no load conditions with those specified, the air box pressures under no load conditions are within the specifications.

2. Catalytic Device Code "X"-2 Results

Catalytic muffler Code "X"-2 was evaluated in municipal bus 678. This vehicle was similar in all respects to Bus 681 and was the other E series powered bus selected. The testing procedure, measurement methods and overall evaluation techniques were the same for this vehicle as with Bus 681. On Table 40 of Appendix E may be found a complete log of tests performed with Bus 678 equipped with "X"-2. Shown on this operating schedule are the dates, test days, test mileages, as well as vehicle/engine maintenance notes. Tables 41 through 56, Appendix E, contain complete results of the initial and final evaluations made with this vehicle. These results are summarized in text Tables 7 through 11, and Figures 4 and 5. The tabular data of Appendix E, as well as the summary tables and figures in the text, are identically constructed to those introduced for vehicle 681. The previous qualifying remarks and descriptive comments regarding the preparation of these tables and the presentation of the evaluation results apply to the "X"-2 results.

---

*Source: GMC Truck and Coach Division Maintenance Manual X-310 dated September 1963.

Table 18 of the text summarizes the odor evaluations conducted with "X"-2 in vehicle 678. Only two inspections were conducted at the end of 40 test days and 5359 test miles (August 16 and 17, 1967--initial inspection) and after 71 test days and 9850 test miles (October 11 and 12, 1967--final inspection). Table 7 lists the overall average odor panel responses first for the standard and then for "X"-2. These results are presented first for the 20-mph cruise, then the 40-mph cruise, followed by the idle, the idle-acceleration and the deceleration condition. A review of the data indicates the catalytic muffler had little positive effect on the perceived odor quality and intensity during conditions I and II, the 20- and 40-mph cruise. The idle results indicate an increase in odor quality and intensity at the initial inspection and a decrease at the final inspection. The idle-acceleration results indicate the most pronounced net reduction in "D" and the four qualities, and appear consistent during both the initial and final tests. This same relative level of net change was also

TABLE 18. OVERALL SUMMARY OF ODOR EVALUATIONS CATALYTIC MUFFLER "X"-2 VS STOCK MUFFLER

Vehicle: Bus 678
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I 20 mph 40 hp	8/17/67	40	5359	Stock	5.8	1.5	1.5	1.4	0.7
	8/16/67			"X"-2	6.8	2.1	1.8	1.6	1.6
				Net Change	+1.0	+0.6	+0.3	+0.2	+0.9
	10/12/67	71	9850	Stock	6.4	2.0	1.6	1.0	1.0
	10/11/67			"X"-2	7.8	2.6	1.8	1.3	1.9
				Net Change	+1.4	+0.6	+0.2	+0.3	+0.9
II 40 mph 40 hp	8/17/67	40	5359	Stock	6.0	1.6	1.6	1.3	1.0
	8/16/67			"X"-2	6.5	1.9	1.6	1.3	1.1
				Net Change	+0.5	+0.3	0	0	+0.1
	10/12/67	71	9850	Stock	6.9	1.7	1.8	1.1	1.2
	10/11/67			"X"-2	6.8	1.9	1.7	1.2	1.3
				Net Change	-0.1	+0.2	-0.1	+0.1	+0.1
III Idle	8/17/67	40	5359	Stock	4.8	1.4	1.2	0.9	0.9
	8/16/67			"X"-2	6.1	1.8	1.6	1.3	1.2
				Net Change	+1.3	+0.4	+0.4	+0.4	+0.3
	10/12/67	71	9850	Stock	8.0	2.7	1.8	1.7	1.7
	10/11/67			"X"-2	6.6	1.9	1.4	1.4	1.2
				Net Change	-1.4	-0.8	-0.4	-0.3	-0.5
IV Idle-Acceleration	8/17/67	40	5359	Stock	6.6	2.1	1.7	1.3	1.4
	8/16/67			"X"-2	5.7	1.9	1.4	1.3	1.3
				Net Change	-0.9	-0.2	-0.3	0	-0.1
	10/12/67	71	9850	Stock	8.2	2.6	1.7	1.7	1.9
	10/11/67			"X"-2	6.7	2.1	1.7	1.2	1.2
				Net Change	-1.5	-0.5	0	-0.5	-0.7
V Deceleration	8/17/67	40	5359	Stock	6.4	1.9	1.4	1.4	1.8
	8/16/67			"X"-2	5.8	1.7	1.3	1.2	1.0
				Net Change	-0.6	-0.2	-0.1	-0.2	-0.8
	10/12/67	71	9850	Stock	8.6	2.7	2.1	1.7	2.2
	10/11/67			"X"-2	6.8	2.2	1.6	1.1	1.3
				Net Change	-1.8	-0.5	-0.5	-0.6	-0.9

noted during condition V, the deceleration after a 40-mph cruise. These summary results are interesting to consider in the form of bar charts. Seen in Figure 23, "X"-2 appears to be effective in reducing the overall diesel odor intensity and quality during conditions IV and V, the idle-acceleration and deceleration. The other three conditions resulted in higher levels of exhaust odor as shown by the relative magnitude of the bars. On Figure 24 are the results of "X"-2 relative to the standard unit as ascertained during the final evaluation. Reductions appear to have been

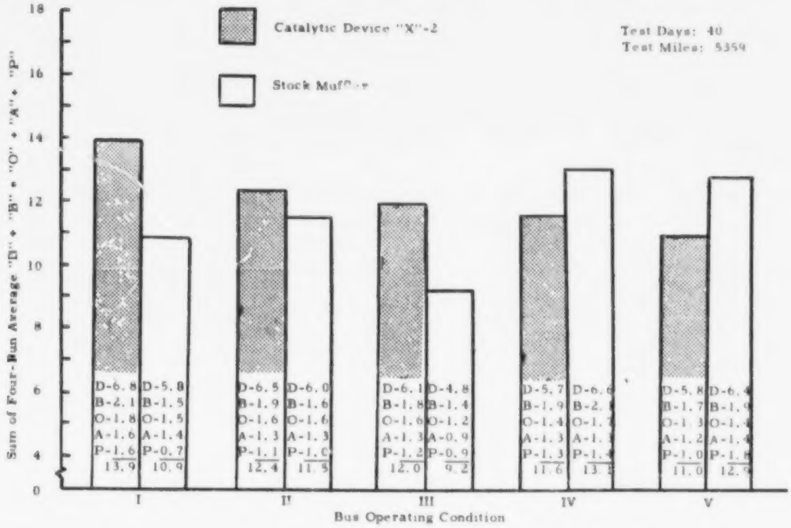


FIGURE 23. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 678, Date: August 16 and 17, 1967)

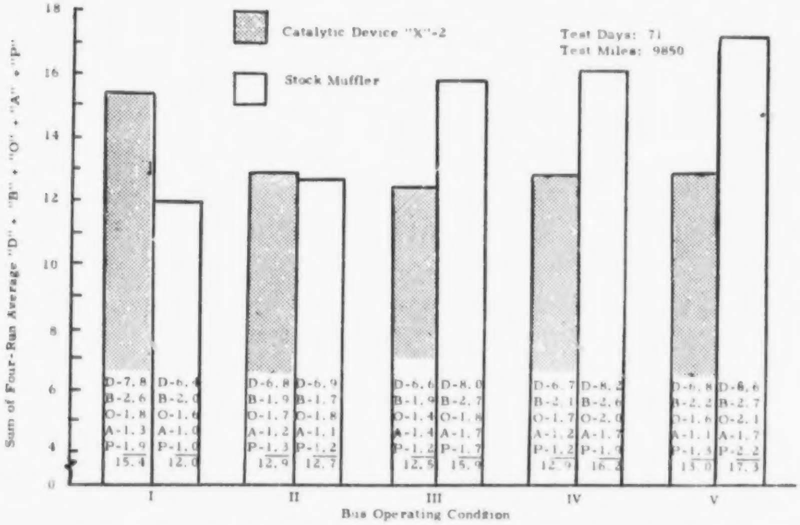


FIGURE 24. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 678, Date: October 11 and 12, 1967) obtained with the catalytic muffler during conditions III, IV, and V. Tables 41 and 49 of Appendix E compare the overall four-run average panel response results with and without the catalytic muffler installed for the initial and final evaluations. These two comparison tables were prepared from summary data listed on Tables 42 and 43 (initial evaluation) and on Tables 50 and 51 (final evaluation). Similar to the odor data presented for Bus 681, each of these summary tables was prepared from five supporting tables known as 42A-42E, 43A-43E, 50A-50E, and 51A-51E for the initial and final sets of measurements.

The results of the "U" statistical analysis applied to the odor evaluations are shown on Table 19 in the text. Only those odor responses with "U" statistic of 0 to 2 were brought forward from the statistical analyses contained in Tables 44 and 52 of Appendix E. These Appendix E tables contain the initial and final statistical analyses for difference in odor measurements for "X"-2

TABLE 19. ODOR RESPONSE U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "X"-2 VS STOCK MUFFLER

Vehicle: Bus 678
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses "D" Composite	 "B" Burnt	 "O" Oily	 "A" Aromatic	 "P" Pungent
I	8/16/67	40	5359	"X"-2	6.8	2.1	*	*	1.6
20 mph	8/17/67			Stock	5.8	1.5			0.7
40 hp	U_s Statistic				2	1			0
	10/11/67	71	9850	"X"-2	7.8	2.6	*	*	1.9
	10/12/67			Stock	6.4	2.0			1.0
	U_s Statistic				0	0			0
II	8/16/67	40	5359	"X"-2	*	*	*	*	*
40 mph	8/17/67			Stock					
40 hp	U_s Statistic								
	10/11/67	71	9850	"X"-2	*	*	*	*	*
	10/12/67			Stock					
	U_s Statistic								
III	8/16/67	40	5359	"X"-2	*	*	*	1.3	*
Idle	8/17/67			Stock				0.9	
	U_s Statistic							0.5	
	10/11/67	71	9850	"X"-2	6.6	1.9	1.4	1.4	1.2
	10/12/67			Stock	8.0	2.7	1.8	1.7	1.7
	U_s Statistic				0	0	2	1	0.5
IV	8/16/67	40	5359	"X"-2	5.7	1.9	1.4	*	*
Idle-	8/17/67			Stock	6.6	2.1	1.7		
Acceleration	U_s Statistic				0	0	0.5		
	10/11/67	71	9850	"X"-2	6.7	*	*	*	*
	10/12/67			Stock	8.2				
	U_s Statistic				2				
V	8/16/67	40	5359	"X"-2	*	*	*	*	1.0
Deceleration	8/17/67			Stock					1.8
	U_s Statistic								0
	10/11/67	71	9850	"X"-2	6.8	2.2	1.6	1.1	1.3
	10/12/67			Stock	8.6	2.7	2.1	1.7	2.2
	U_s Statistic				0.5	2	1	1	1

*U_s statistic greater than 2, no statistical difference apparent.

relative to the stock muffler. According to Table 19 in the text, a statistical difference was indicated for the "D," "B," and "P" qualities at the 20-mph condition during both initial and final evaluations. The exhaust from the catalytic muffler, however, was of higher intensity in all cases than that perceived from the stock muffler. Under condition II, the 40-mph cruise, no statistical difference was indicated for either the initial or final measurements. The consistent reduction in "D," as well as the four qualities, was indicated during the final evaluation at the idle condition. For condition IV, the acceleration, a statistical difference was indicated during the initial evaluation for "D," "B," and "O," and during the final evaluation for "D" only. The deceleration condition, condition V, resulted in a decrease in all five of the odor ratings during the final evaluation. When these statistical differences were viewed in light of the bar charts shown on Figures 23 and 24, it was apparent that fairly large relative bar chart differences correspond nicely with those instances identified by the "U" statistic.

Table 20 presents the average PHS smoke reading in percent opacity for the four constant speed, open-rack operating conditions and then for three portions of the idle-acceleration of interests. Considering the data listed in the smoke reduction column, little or no improvement in exhaust smoke was measured under the 20-, 25-, 30- and 35-mph maximum power output conditions. Similarly, only a slight reduction in visible smoke was recorded during the idle-acceleration condition. Since smoke readings on engine start represent one black puff or a single meter deflection, significance should not be placed in the engine start data. Most diesel engines in municipal bus service are not repeatedly started. A reduction of over 5-percent opacity was recorded during the final evaluation during acceleration from 0 mph. Except for this smoke difference noted, the catalytic muffler appears to have only a slight effect on smoke during acceleration. The smoke data summarized on Table 20 were based on smoke readings listed on Tables 45 and 53 of Appendix E for the initial and final evaluations.

TABLE 20. OVERALL SUMMARY OF SMOKE EVALUATIONS
CATALYTIC MUFFLER "X"-2 VS STOCK MUFFLER

Vehicle: Bus 678
Fuel: EM-3A-F

Operating Conditions: See Tables 7 through 9 in Appendix E

Dates Evaluated: See below.

Constant Speed (All open rack - maximum power output):

Operating Conditions	Vehicle Speed, mph	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, Percent Opacity
					Stock	"X"-2	
A	20	8/14,17/67	40	5359	16.7	16.3	0.4
		10/10,12/67	71	9850	20.6	22.3	(1.7)*
B	25	8/14,17/67	40	5359	13.0	13.2	(0.2)
		10/10,12/67	71	9850	16.5	17.2	(0.7)
C	30	8/14,17/67	40	5359	12.5	12.2	0.3
		10/10,12/67	71	9850	15.0	14.2	0.8
E	35	8/14,17/67	40	5359	10.2	10.0	0.2
		10/10,12/67	71	9850	12.6	11.7	0.9

Idle-Acceleration (40 hp at 30 mph preset and retained):

Portion of "E" Idle-Acceleration	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, Percent Opacity
				Stock	"X"-2	
Engine Start	8/14,17/67	40	5359	16.2	12.5	3.7
	10/10,12/67	71	9850	17.0	9.7	7.3
During Acceleration	8/14,17/67	40	5359	9.3	8.0	1.3
	10/10,12/67	71	9850	14.7	9.3	5.4
After Upshift	8/14,17/67	40	5359	12.7	11.0	1.7
	10/10,12/67	71	9850	13.7	12.0	1.7

---

*( ) indicates increase in smoke with catalytic muffler installed.

The average "as-measured" exhaust emissions and muffler pressure and temperature measurements are summarized on Table 21 in the text. This table summarizes the average results by operating condition and test date. Discussing the exhaust emissions first, the carbon monoxide values were the same or slightly higher when the vehicle was equipped with the catalytic muffler.

TABLE 21. SUMMARY OF AVERAGE "AS-MEASURED" EXHAUST EMISSIONS AND MUFFLER PRESSURE AND TEMPERATURE MEASUREMENTS CATALYTIC MUFFLER CODE "X"-2 VS STOCK MUFFLER

Vehicle: Bus 678
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions:
Exhaust Emissions: See Table 10
Muffler Pressure and Temperature: See Table 11 & 12

Average "As-Measured" Exhaust Emissions

Operating Conditions	Test Date	Test Days	Test Miles	CO, ppm		CO_2, percent		Acrolein, ppm		Aliphatic Aldehydes, ppm*		Formaldehyde, ppm		NO_x, ppm NO_2		SO_2, ppm		Adjusting Factor†	
				Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2
I 20 mph 40 hp	8/15, 18/67 10/10, 13/67	40 71	5,359 9,050	370 300	460 445	5.9 4.5	5.5 5.2	6.32 3.92	3.71 5.17	21.2 25.7	28.4 28.9	16.5 13.5	30.65 17.40	725 576	692 570	1.24 0.36	0.74 0.84	2.52 3.31	2.70 2.86
II 40 mph 40 hp	8/15, 18/67 10/10, 13/67	40	5,359 11,829	205 195	205 185	4.1 3.50	4.0 3.85	3.23 2.46	2.45 2.29	18.8 22.7	20.1 21.6	14.9 8.05	17.4 13.6	452 375	450 352	0.89 0.67	1.10 0.75	3.64 4.28	3.73 3.93
III Idle	8/15, 18/67 10/10, 13/67	40 88	5,359 11,829	305 210	290 270	1.0 1.1	1.0 1.1	5.78 5.47	3.16 3.28	26.6 34.1	26.3 31.7	19.2 17.7	25.15 21.2	169 116	173 147	0.13 0.11	0.40 0.21	14.5 13.35	14.55 13.30

Average Muffler Pressure and Temperature Measurements

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Pressure, in. Hg						Muffler Temperature, °F						Air Box Pressure, in. Hg	
				Inlet		Outlet		Differential		Inlet		Outlet		Differential			
				Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2	Stock	"X"-2
I 20 mph 40 hp	8/16, 17/67 10/11, 12/67	40 88	5,359 11,829	1.0 0.9	1.0 0.85	0.25 0.30	0.35 0.35	0.75 0.60	0.60 0.50	572 522	539 508	466 441	431 361	106 81	108 177	1.4 1.7	1.6 1.6
II 40 mph 40 hp	8/16, 17/67 10/11, 12/67	40 88	5,359 11,829	3.5 3.2	3.2 3.2	0.95 1.2	1.35 1.3	2.6 2.0	1.75 1.80	567 561	560 542	549 904	528 495	18 57	32 47	7.2 6.8	7.0 6.9
III Idle	8/16, 17/67 10/11, 12/67	40 88	5,359 11,829	0.25 0.30	0.30 0.30	0.05 0.10	0.10 0.10	0.2 0.2	0.2 0.2	319 292	312 276	342 322	351 412	23 30	39 136	0.7 1.3	0.9 1.2
IIIa 30 mph 40 hp	8/16, 17/67 10/11, 12/67	40 88	5,359 11,829	2.0 1.85	1.75 1.75	0.55 0.75	0.7 0.75	1.45 1.1	1.05 1.0	554 503	519 498	477 439	453 392	77 64	66 106	3.7 3.6	3.7 3.4

---

*Total as ppm formaldehyde.

†Adjusting factor is computed by dividing 15 by the percent (CO and CO_2) in the exhaust using "as-measured" average CO and CO_2 measurements.

This seemed particularly evident during the 20-mph cruise in which the "X"-2 CO concentrations ranged from 90 to 145 ppm greater than that from the stock muffler. Carbon dioxide values were essentially the same except during the 20-mph condition. The "X"-2 muffler CO_2 concentration was lower, initially, and higher, finally, than the stock muffler. This same type of reversal for condition I was also noted for acrolein in which the initial results indicated that acrolein was lower initially with the "X"-2 muffler and higher finally with the catalytic unit relative to the standard muffler. During conditions II and III, the 40-mph cruise and the idle, the acrolein values were always less than those from the stock muffler. The aldehydes and formaldehyde from "X"-2 were higher than those from the stock muffler during both initial and final evaluations at 20 mph. For the 40-mph cruise, the aldehyde concentrations were essentially the same with or without the catalytic muffler during initial and final evaluations. Formaldehyde appeared to increase slightly during the initial and final evaluation for the catalytic muffler. Considering the idle data, the total aldehydes were approximately the same regardless of muffler configuration. Formaldehyde appeared to increase slightly when the vehicle was equipped with "X"-2 muffler during both initial and final evaluations. Oxides of nitrogen appeared to be unaffected by muffler configuration regardless of operating condition. The slight increase in NO_x, as ppm NO_2, was noted for the catalytic muffler at the final idle evaluation. Sulfur dioxide values appeared to be about the same in magnitude and scatter as those mentioned for Bus 681. During the initial evaluation at 20 mph, SO_2 appeared to be reduced, but, during the final evaluation, SO_2 appeared to be increased by the "X"-2 muffler. Increases were also noted in SO_2 during the idle during both initial and final evaluations. In the last column of Table 21 may be found adjusting factors which can be used to normalize the stock and "X"-2 muffler emissions data. For additional "as-measured" and adjusted average exhaust emissions, please refer to Table 46 (initial evaluation) and Table 54 (final evaluation) in Appendix E.

Statistical analyses of the "as-measured" exhaust emissions are shown in Tables 47 and 55 of Appendix E. Listed on Table 22 of the text are those instances in which the "U" statistic screening test indicated a statistical difference in the measured data. To assist in discussing whether the statistical difference may be considered a significant difference, the average "as-measured" emissions values are also listed. Considering condition I, the 20-mph cruise, a statistical difference was indicated for CO and acrolein during the initial and final evaluations.

TABLE 22. EXHAUST EMISSIONS U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "X"-2 VS STOCK MUFFLER

Vehicle: Bus 678
Fuel: EM-3A-F

Operating Conditions: See Tables 10 & 14 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average "As-Measured" Exhaust Emissions						
					CO, ppm	CO_2, percent	Acrolein, ppm	Aldehydes, ppm Form.	Formaldehyde, ppm	NO_x, ppm	SO_2, ppm
I	8/15/67	40	5359	"X"-2	460	*	3.71	28.4	*	*	0.74
20 mph	8/18/67			Stock	370		6.32	21.2			1.24
40 hp	U_s Statistic				0		0	2			1
	10/10/67	71	9850	"X"-2	445	*	5.17	*	17.4	*	*
	10/12/67			Stock	300		3.92		13.5		
	U_s Statistic				0		1		2		
II	8/15/67	40	5359	"X"-2	*	*	2.45	*	*	*	*
40 mph	8/18/67			Stock			3.23				
40 hp	U_s Statistic						0				
	10/10/67	71	9850	"X"-2	185	*	2.29	*	13.6	*	*
	10/12/67			Stock	155		2.46		8.85		
	U_s Statistic				1		2		0		
III	8/15/67	40	5359	"X"-2	290	*	3.16	*	25.15	*	0.40
Idle	8/18/67			Stock	305		5.78		19.2		0.13
	U_s Statistic				0		0		1		0
	10/10/67	71	9850	"X"-2	270	*	3.28	*	21.2	147	0.21
	10/12/67			Stock	210		5.47		17.7	116	0.11
	U_s Statistic				0		0		1.5	0.5	1.5

---

*U_s statistic greater than 2, no statistical difference apparent.

It is not known why the CO values were greater with "X"-2 relative to the stock muffler. Acrolein values during this 20-mph cruise were different and were so indicated statistically. In one case, the initial evaluation, this difference was shown as a decrease in acrolein for "X"-2. In the final evaluation, the difference related to a slight increase in acrolein with "X"-2. The increase in aldehydes noted during the initial inspection at 20 mph was identified as a statistical difference, although the increase of 7 ppm may not be significant. Likewise, the increase in formaldehyde during the final 20-mph cruise does not appear significant. The reduction in sulfur dioxide found during the initial 20-mph inspection must be viewed with respect to the scatter of data.

In a few instances, the exhaust emissions were noted as statistically different during the 40-mph cruise condition. The only significant instance, however, appeared to be an increase in formaldehyde with the "X"-2 muffler, found during the final inspection. A number of emissions appeared to be statistically different as measured during the idle condition. The slight difference in carbon monoxide, though statistically different, does not warrant special consideration. The apparent improvement in acrolein during the idle condition was found to be different statistically. This reduction may be adjudged significant, from the approximately 50-percent reduction shown, which was consistent during the initial and final evaluations. In the other direction, however, the formaldehyde concentrations appeared to be consistently greater with the "X"-2 muffler relative to the stock unit. The slight difference in oxides of nitrogen noted during the final idle test should not be considered significant nor do the sulfur dioxide differences warrant special consideration.

Shown on the lower portion of text Table 21 is a summary of the average muffler pressure and temperature measurements. Basically, the same comments may be made regarding the data for each of the operating conditions evaluated as was presented for Bus 681 equipped with Code "X"-1 muffler. From a review of the average data listed, the differential pressure drop across the stock or catalytic muffler was nearly identical under the idle, 20-, 40-, and 30-mph cruise conditions studied. The inlet and outlet muffler temperatures appear to be similar to those obtained with the "X"-1 muffler. The catalytic muffler generally reduced the outlet temperature more than the stock muffler did and thereby resulted in a greater differential temperature across the unit. Under the 20-, 40-, and 30-mph cruise conditions, the characteristic of the stock muffler and the catalytic muffler was basically the same, i.e., a drop in temperature across the muffler. In the case of the idle condition, which was preceded by the 30-mph, 40-hp cruise condition, the differential temperatures represented a temperature rise. The engine air box pressures indicated no abnormal engine air breathing during the four odor operating conditions investigated. These pressures, as well as the muffler and exhaust system backpressure, were within the manufacturer's recommendations. Pressure and temperature data shown on Table 21 were prepared from measurements listed in Tables 48 and 56, Appendix E, for the initial and final evaluations. Air box pressures under no load condition, at 1200-, 1800-, and 2100-rpm engine speed, are also included.

3. Catalytic Device Code "X"-3 Results

The third and final Code "X" catalytic muffler, identified as "X"-3, was evaluated in Bus 768, a GM Truck and Coach municipal bus identical to Buses 681 and 678. The only gross difference between Bus 768 and the two previously discussed vehicles was that it was newer and powered by the later, N series, version of the Detroit Diesel 6V-71 two-cycle engine. The major difference between the N series and E series engine, described on Table 1 of Appendix E, is an increase in compression ratio from 17:1 to 18.7:1 and the use of the N type fuel injectors of same delivery capacity but with different delivery characteristics than the S type injector used in the E version. The "X"-3 device was, as far as known, identical to the other two Code "X" mufflers evaluated.

A complete operating log listing the test intervals, test dates, mileage accumulation and pertinent maintenance notes may be found on Table 57 of Appendix E. The evaluations were performed according to the operating conditions and procedures for odor, smoke, exhaust emissions and pressures and temperatures previously introduced. Shown on Table 23 of the text is an overall summary of odor evaluations performed with "X"-3 for the initial, interim and final inspections. These summary results are grouped by operating condition and list the stock, catalytic, and net change for each of the three inspection periods chronologically. The initial test and inspection were conducted during August 21-25, 1967, after 39 test days and 6277 test miles. The interim evaluation was performed during September 24-29, 1967, after 69 test days and 11,495 test miles. The final round of tests was conducted on October 30-November 3 after 101 test days and 18,639 test miles.

Considering the 20-mph cruise, condition I, the catalytic and stock muffler resulted in approximately the same perceived odor quality and intensity during all three evaluations. Essentially, the same statement may be made regarding the 40-mph cruise results, condition II. The idle results, however, seemed to indicate a slight reduction in "D" and the four qualities for "X"-3. These consistent though minor differences indicate the catalytic muffler was effective in this regard. Comparing the catalytic muffler with the stock muffler during condition IV, the acceleration, consistent slight reductions were found during the initial and interim vehicle inspections. This trend was not consistent, however, in that the net changes, though minor in level, were in favor of the stock muffler during the final inspection. Little or no net change was found for "X"-3 during the deceleration condition, and this result seemed consistent throughout all three evaluations.

The odor data shown on the Table 23 summary were graphed in Figures 25, 26 and 27 for the initial, interim and final evaluations, respectively. Considering these three bar charts along with Table 23, it is apparent that during the initial evaluation, the catalytic muffler appeared to have some effect during conditions I and IV. Under the other three conditions, the catalytic muffler

TABLE 23. OVERALL SUMMARY OF ODOR EVALUATIONS CATALYTIC MUFFLER "X"-3 VS STOCK MUFFLER

Vehicle: Bus 768
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	8/24/67	39	6,277	Stock	5.5	1.7	1.4	0.9	0.7
20 mph	8/23/67			"X"-3	5.2	1.4	1.0	1.0	0.7
40 hp				Net Change	-0.3	-0.3	-0.4	+0.1	0
	9/27/67	69	11,495	Stock	5.1	1.6	1.4	0.9	0.6
	9/26/67			"X"-3	5.2	1.6	1.2	1.0	0.8
				Net Change	+0.1	0	-0.2	+0.1	+0.2
	11/2/67	101	18,639	Stock	5.4	1.5	1.2	0.7	0.8
	11/1/67			"X"-3	6.0	1.8	1.3	1.1	0.8
				Net Change	+0.6	+0.3	+0.1	+0.4	0
II	8/24/67	39	6,277	Stock	5.1	1.6	1.2	0.8	0.4
40 mph	8/23/67			"X"-3	5.0	1.2	0.9	1.2	0.5
40 hp				Net Change	-0.1	-0.4	-0.3	+0.4	+0.1
	9/27/67	69	11,495	Stock	4.9	1.5	1.2	0.9	0.7
	9/26/67			"X"-3	5.1	1.6	1.2	0.9	0.4
				Net Change	+0.2	+0.1	0	0	-0.3
	11/2/67	101	18,639	Stock	5.3	1.5	1.2	0.9	0.8
	11/1/67			"X"-3	5.8	1.7	1.3	0.9	0.9
				Net Change	+0.5	+0.2	+0.1	0	+0.1
III	8/24/67	39	6,277	Stock	4.6	1.3	0.9	0.8	0.4
Idle	8/23/67			"X"-3	4.6	1.0	0.8	1.0	0.7
				Net Change	0	-0.3	-0.1	+0.2	+0.3
	9/27/67	69	11,495	Stock	5.2	1.6	1.3	1.0	0.8
	9/26/67			"X"-3	4.5	1.2	1.0	0.9	0.5
				Net Change	-0.7	-0.4	-0.3	-0.1	-0.3
	11/2/67	101	18,639	Stock	5.9	1.8	1.4	1.1	1.0
	11/1/67			"X"-3	5.1	1.5	1.0	0.9	0.7
				Net Change	-0.8	-0.3	-0.4	-0.2	-0.3
IV	8/24/67	39	6,277	Stock	6.6	2.0	1.8	1.1	1.3
Idle-Acceleration	8/23/67			"X"-3	6.2	1.9	1.3	1.4	1.0
				Net Change	-0.4	-0.1	-0.5	+0.3	-0.3
	9/27/67	69	11,495	Stock	6.6	2.1	1.8	1.2	1.5
	9/26/67			"X"-3	5.7	1.8	1.5	1.2	1.0
				Net Change	-0.9	-0.3	-0.3	0	-0.5
	11/2/67	101	11,639	Stock	6.1	1.7	1.5	0.9	1.0
	11/1/67			"X"-3	6.6	2.1	1.6	1.3	1.2
				Net Change	+0.5	+0.4	+0.1	+0.4	+0.2
V	8/24/67	39	6,277	Stock	4.8	1.4	1.0	0.6	0.5
Deceleration	8/23/67			"X"-3	5.1	1.6	1.1	0.9	0.5
				Net Change	+0.3	+0.2	+0.1	+0.3	0
	9/27/67	69	11,495	Stock	3.8	1.0	0.9	0.6	0.4
	9/26/67			"X"-3	4.9	1.5	1.1	1.1	0.7
				Net Change	+1.1	+0.5	+0.2	+0.5	+0.3
	11/2/67	101	18,639	Stock	4.9	1.2	1.0	0.7	0.5
	11/1/67			"X"-3	5.0	1.2	1.0	0.7	0.2
				Net Change	+0.1	0	0	0	-0.3

appeared to lack noticeable improvement. The bar graph of the interim odor evaluation, Figure 26, illustrates that the catalytic muffler appeared to be somewhat effective under conditions III and IV, the idle and idle-acceleration, but lacked effectiveness during the deceleration condition, condition V. Shown on Figure 27 is a similar comparison for "X"-3 versus the stock muffler in which "X"-3 continues to noticeably reduce the exhaust odor under condition III. Under all other conditions, the catalytic muffler either lacked effectiveness or resulted in slightly higher readings. Considering Figures 25 through 27 together, the catalytic muffler appeared to reduce the diesel exhaust odor by about the same amount during the interim and final inspection. Although the initial and interim results under the idle-acceleration indicated a reduction in perceived odor, this reduction was not consistent. All other conditions appeared to have mixed results and lacked consistency or apparent positive

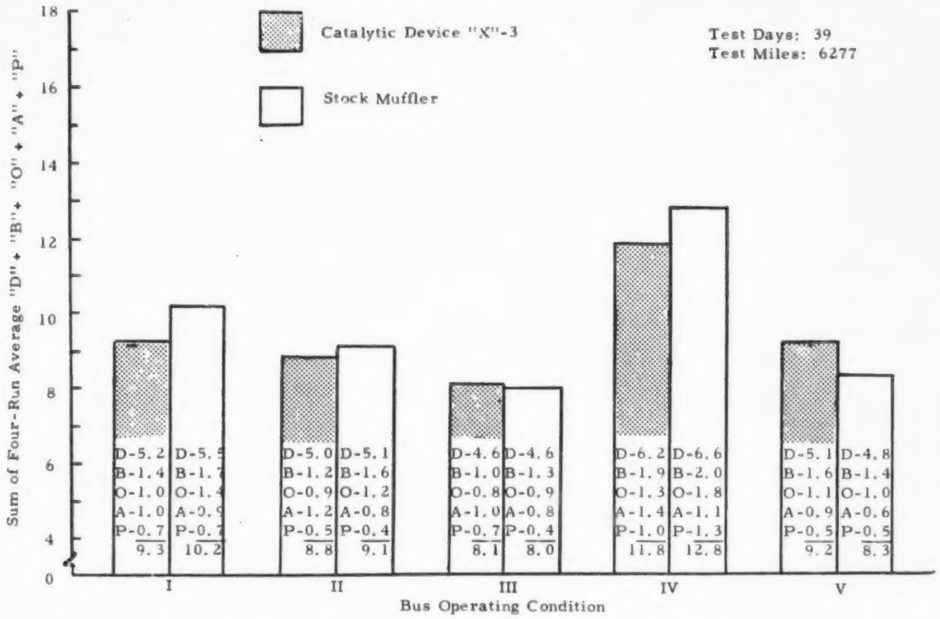


FIGURE 25. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 768, Date: August 23 and 24, 1967)

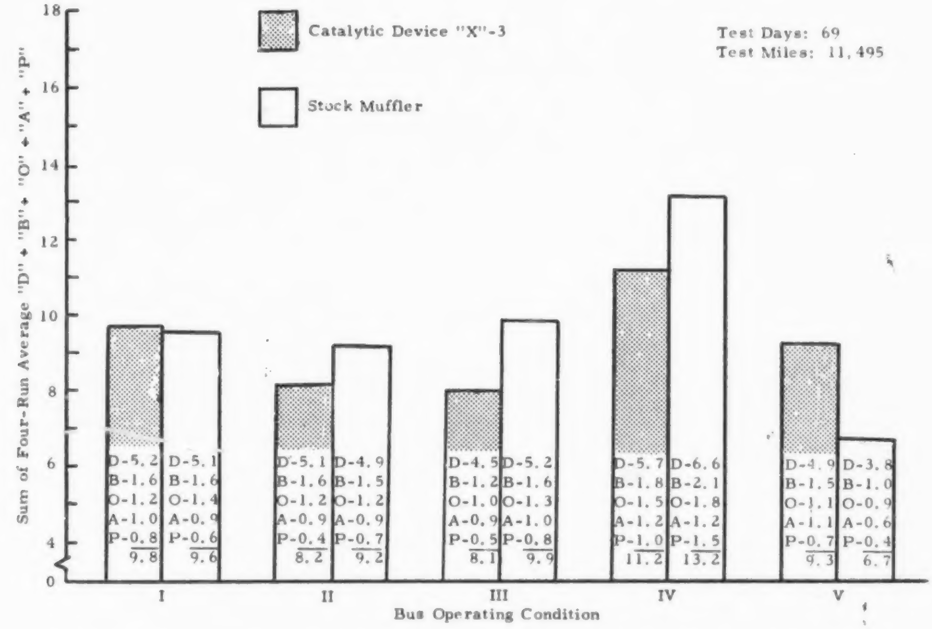


FIGURE 26. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 768, Date: September 26 and 27, 1967)

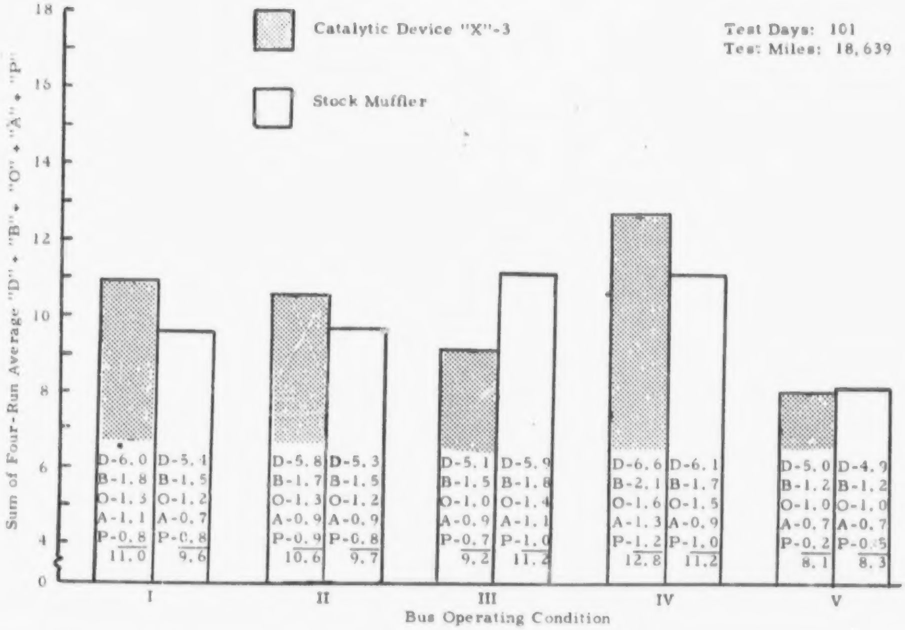


FIGURE 27. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 768, Date: November 1 and 2, 1967)

trends. This summary was based on extensive odor evaluations listed in Appendix E. The initial results are compared on Table 58 from averaged results on Tables 59 and 60 of Appendix E. Tables 59 and 60 were prepared from Tables 59A-59E and 60A-60E which list the panel responses for each of the twenty-four runs. These tables are furnished to provide sufficient information and data to reveal the distribution of the panel responses for each run and each of the five odor constituents evaluated. In similar fashion, Table 66 lists the interim results drawn from the 4-day averages listed on Tables 67 and 68 of Appendix E. Odor response distributions are indicated in Tables 67A-67E and 68A-68E. Likewise, the final evaluation data are included on Tables 74 through 76 of Appendix E. Please refer to these detailed tabulations of the odor panel evaluations, their responses, response distribution, and arithmetic average results.

Summarized on Table 24 in the text are the pertinent results of the U_s screening analysis to determine statistical difference of "X"-3 versus stock muffler data. Only those values were brought forward from the statistical analyses included in Appendix E which were felt to show a statistical difference, i.e., U_s equal to 0-2. Considering the 20-mph cruise, condition I, there was essentially no statistical difference indicated for the perceived exhaust odor between the "X"-3 and stock muffler. Only during the final evaluation was there a statistical difference indicated; a slight increase in "D" with the "X"-3 muffler. An even less number of instances were shown to be statistically different during the initial, interim and final evaluations under the 40-mph cruise condition. Slight changes in "B" and "A" noted at the interim evaluation are considered to be negligible.

Considering the significance of the differences noted between the "X"-3 and stock muffler under condition III, the idle, only during the interim evaluation was there a statistically different "D" rating. This difference was noted between a stock "D"-5.2 rating relative to the "X"-3 "D" rating of 4.5. The other differences noted were generally in favor of the "X"-3 muffler but were in odor qualities which carry less significance than the overall "D" composite. Considering the idle-acceleration condition, the overall effectiveness of "X"-3 was evident in the "D" category only during the interim evaluation. A statistical difference was identified by the stock "D"-6.6 rating

TABLE 24. ODOR RESPONSE U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "X"-3 VS STOCK MUFFLER

Vehicle: Bus 768
Fuel: EM-3A-F

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average Odor Panel Responses				
					"D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I 20 mph 40 hp	8/23/67 8/24/67 U_s Statistic	39	6,277	"X"-3 Stock	*	*	1.0 1.4 1	*	*
	9/26/67 9/27/67 U_s Statistic	69	11,495	"X"-3 Stock	*	*	*	*	*
	11/1/67 11/2/67 U_s Statistic	101	18,639	"X"-3 Stock	6.0 5.4 2	*	*	1.1 0.7 0.5	*
II 40 mph 40 hp	8/23/67 8/24/67 U_s Statistic	39	6,277	"X"-3 Stock	*	1.2 1.6 0.5	*	1.2 0.8 0	*
	9/26/67 9/27/67 U_s Statistic	69	11,495	"X"-3 Stock	*	*	*	*	*
	11/1/67 11/2/67 U_s Statistic	101	18,639	"X"-3 Stock	* 1	*	*	*	*
III Idle	8/23/67 8/24/67 U_s	39	6,277	"X"-3 Stock	*	*	*	1.0 0.8 0.5	*
	9/26/67 9/27/67 U_s Statistic	69	11,495	"X"-3 Stock	4.5 5.2 2	*	1.0 1.3 2	*	*
	11/1/67 11/2/67 U_s Statistic	101	18,639	"X"-3 Stock	*	1.5 1.8 2	1.0 1.4 0	0.9 1.1 0.5	*
IV Idle-Acceleration	8/23/67 8/24/67 U_s Statistic	39	6,277	"X"-3 Stock	*	*	1.3 1.8 1	*	*
	9/26/67 9/27/67 U_s Statistic	69	11,495	"X"-3 Stock	5.7 6.6 2	1.8 2.1 0.5	*	*	1.0 1.5 0
	11/1/67 11/2/67 U_s Statistic	101	18,639	"X"-3 Stock	*	*	*	1.3 0.9 0.5	*
V Deceleration	8/23/67 8/24/67 U_s Statistic	39	6,277	"X"-3 Stock	*	1.6 1.4 2	1.1 1.0 0.5	*	*
	9/26/67 9/27/67 U_s Statistic	69	11,495	"X"-3 Stock	4.9 3.8 0	1.5 1.0 0	1.1 0.9 0.5	1.1 0.6 0.5	0.7 0.4 0.5
	11/1/67 11/2/67 U_s Statistic	101	18,639	"X"-3 Stock	*	*	*	*	*

---

*U_s statistic greater than 2, no statistical difference apparent.

being reduced to a "D"-5.7 with the "X"-3 unit. This was accompanied by a reduction in "B" from a "B"-2.1 to a "B"-1.8 and a reduction in "P" from 1.5 to 1.0. The results of the statistical analysis of the initial and final idle-acceleration data indicated no significant or important difference between the "X"-3 and the stock muffler exhaust odor. A statistical difference "across-the-board" was noted for the interim deceleration condition. This statistical difference was found, however, in an instance in which the exhaust from the catalytic muffler equipped vehicle had a higher "D," "B," "O," "A," and "P" rating than that with the stock muffler. This was the only substantial statistical difference indicated during the three muffler evaluations conducted under condition V. For additional details regarding the statistical analyses summarized on Table 24, please refer to Tables 61, 69 and 77 of Appendix E for the initial, interim, and final evaluations.

Shown on Table 25 of the text is an overall summary of the smoke evaluations. The upper half of the table is devoted to the constant speed maximum power, open-rack conditions at 20, 25, 30 and 35 mph. The stock and "X"-3 readings are listed chronologically by test date, test days, and test miles. Considering the constant speed results, little or no improvement in smoke was effected by "X"-3 except during the final evaluation in which a consistent reduction was indicated. The reason for this level of improvement of approximately 5- to 6-percent opacity is not certain. The test readings may be in slight error even though conducted in triplicate with the same smokemeter and associated test apparatus. It is difficult, however, to place great importance in this single instance when the initial and interim data indicated apparent ineffectiveness. Considering the idle-acceleration smoke reductions listed, the catalytic and stock mufflers resulted in approximately the same level of smoke during the initial and interim evaluations. This was not the case during the final evaluation in which the visible smoke was reduced by about 3-percent opacity. Contained on Tables 62, 70 and 78 of Appendix E are comparisons of the smoke emissions for the initial, interim, and final inspections. Please refer to these tables for additional information regarding smoke and power measurements.

TABLE 25. OVERALL SUMMARY OF SMOKE EVALUATIONS CATALYTIC MUFFLER "X"-3 VS STOCK MUFFLER

Vehicle: Bus 768
Fuel: EM-3A-F

Operating Conditions: See Tables 7 through 9 in Appendix E

Dates Evaluated: See below.

Constant Speed (All open rack - maximum power output):

Operating Conditions:	Vehicle Speed, mph	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, Percent Opacity
					Stock	"X"-3	
A	20	8/22,24/67	39	6,277	12.5	12.3	0.2
		9/25,27/67	69	11,495	13.7	16.0	(2.3)*
		10/31; 11/2/67	101	18,639	20.0	13.7	6.3
B	25	8/22,24/67	39	6,277	9.0	8.8	0.2
		9/25,27/67	69	11,495	6.1	10.3	(4.2)
		10/31; 11/2/67	101	18,639	15.3	8.7	6.6
C	30	8/22,24/67	39	6,277	8.0	8.0	0
		9/25,27/67	69	11,495	7.3	8.5	(1.2)
		10/31; 11/2/67	101	18,639	13.3	7.8	5.5
D	35	8/22,24/67	39	6,277	5.5	6.2	(0.7)
		9/25,27/67	69	11,495	4.7	5.7	(1.0)
		10/31; 11/2/67	101	18,639	10.3	5.2	5.1

Idle-Acceleration (40 hp at 30 mph preset and retained):

Portion of "E" Idle-Acceleration	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, Percent Opacity
				Stock	"X"-3	
Engine Start	8/22,24/67	39	6,277	2.6	2.0	0.6
	9/25,27/67	69	11,495	1.9	2.7	(0.8)
	10/31; 11/2/67	101	18,639	4.3	1.0	3.3
During Acceleration	8/22,24/67	39	6,277	7.0	4.7	2.3
	9/25,27/67	69	11,495	8.4	5.7	2.7
	10/31, 1[illegible]/67	101	18,639	9.0	6.0	3.0
After Upshift	8/22,24/67	39	6,277	9.6	7.7	1.9
	9/25,27/67	69	11,495	8.4	10.0	(1.6)
	10/31; 11/2/67	101	18,639	11.7	8.7	3.0

---

*( ) indicates increase in smoke with catalytic muffler installed.

Shown on Table 26 of the text is an overall summary of the average "as-measured" exhaust emissions and muffler pressures and temperatures. Comparing the two sets of average "as-measured" carbon monoxide data, a slight, almost negligible increase in CO was noted with "X"-3. This trend was apparent during all evaluations under all three constant speed conditions. The initial evaluation acrolein values were the same or slightly increased with the "X"-3 muffler for all three conditions. The interim inspection revealed about the same or slightly lower acrolein values. Overall, there appeared to be little net or consistent gross change in acrolein emissions. One instance, the final 40-mph cruise inspection, indicated approximate doubling of the acrolein from 0.4 to 0.90 ppm, however. The initial and interim evaluations revealed the total aliphatic aldehydes were reduced consistently under all three conditions. The aldehyde measurements obtained during the final evaluation, however, were approximately the same for both the stock and catalytic units. Formaldehyde appeared to be reduced in a number of instances, notably the interim 20- and 40-mph cruise conditions. Under other operating conditions and instances, formaldehyde reductions were inconsistent. Considering the average "as-measured" oxides of nitrogen values, "X"-3 had little, if any, noticeable effect on this exhaust constituent. A review of these data indicates fairly close agreement and no significant trends. Sulfur dioxide measurements are shown next and indicate, for all evaluations and conditions, that SO_2 was less than that measured with the stock muffler. As may be seen from Table 26, the differences varied but were always in favor of the catalytic muffler. The adjusting factor listed in the last two columns may be used to normalize the "as-measured" exhaust emissions. Tables 63, 71 and 79 in Appendix E list the individual run results, the four-run averages, and normalized four-run averages adjusted for exhaust air dilution.

TABLE 26. SUMMARY OF AVERAGE "AS-MEASURED" EXHAUST EMISSIONS AND MUFFLER PRESSURE AND TEMPERATURE MEASUREMENTS CATALYTIC MUFFLER CODE "X"-3 VS STOCK MUFFLER

Vehicle: Bus 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions:
Exhaust Emissions: See Table 10
Muffler Pressure and Temperature: See Table 11 & 12

Average "As-Measured" Exhaust Emissions

Operating Conditions	Test Date	Test Days	Test Miles	CO, ppm		CO_2, percent		Acrolein, ppm		Aliphatics Aldehydes, ppm*		Formaldehyde, ppm		NO_x, ppm NO_2		SO_2, ppm		Adjusting Factor†	
				Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3
I	8/22,25/67	39	6,277	150	165	5.4	5.8	1.17	1.22	40.0	21.05	11.80	10.60	487	865	1.8	1.46	2.77	2.58
20 mph	9/25,28/67	69	11,495	125	150	5.05	4.7	1.41	1.16	11.2	10.2	7.20	3.86	812	764	1.23	0.34	2.96	3.18
40 hp	10/31, 11/3/67	101	18,639	125	153	4.3	4.3	0.40	1.15	12.4	14.3	2.52	3.92	820	754	0.90	0.28	3.48	3.48
II	8/22,25/67	39	6,277	90	130	4.4	4.15	1.15	1.56	24.2	15.2	6.6	7.3	585	530	1.6	1.14	3.42	3.60
40 mph	9/25,28/67	69	11,495	70	[illegible]	3.95	3.75	0.87	0.81	10.5	6.61	6.3	3.2	490	485	1.24	0.32	3.8	4.0
40 hp	10/31, 11/3/67	101	18,639	60	65	3.45	3.50	0.48	0.90	12.75	14.0	1.98	3.39	522	503	0.97	0.25	4.35	4.29
III	8/22,25/67	39	6,277	90	115	1.1	1.15	0.80	0.97	21.2	14.0	5.0	5.3	211	232	0.50	0.40	13.5	12.9
Idle	9/25,28/67	69	11,495	80	95	1.1	1.1	0.70	0.75	10.8	8.6	4.3	4.0	185	194	0.54	0.18	13.5	13.5
	10/31, 11/3/67	101	18,639	75	60	1.1	1.1	0.78	0.85	13.7	13.5	3.42	4.75	251	244	0.36	0.17	13.5	13.55

Average Muffler Pressure and Temperature Measurements

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Pressure, in. Hg						Muffler Temperature, °F						Air Box Pressure, in. Hg	
				Inlet		Outlet		Differential		Inlet		Outlet		Differential			
				Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3	Stock	"X"-3
I	8/23,24/67	39	6,277	0.9	1.0	0.4	0.15	0.5	1.1	581	558	504	453	77	105	1.55	1.9
20 mph	9/26,27/67	69	11,495	0.7	1.0	0.3	0.[illegible]	0.4	0.8	478	498	420	414	58	84	1.50	1.9
40 hp	11/1,2/67	101	18,639	0.8	1.0	0.3	0.2	0.4	0.8	478	496	418	411	60	87	1.55	1.9
II	8/23,24/67	39	6,277	3.1	3.8	1.55	0.65	1.50	2.6	561	532	523	514	38	18	8.3	8.2
40 mph	9/26,27/67	69	11,495	2.85	3.4	1.35	0.6	1.45	2.7	534	527	504	466	30	61	8.0	8.5
40 hp	11/1,2/67	101	18,639	2.8	3.3	1.3	0.6	1.5	2.6	526	525	466	452	60	74	8.0	8.4
III	8/23,24/67	39	6,277	0.2	0.2	0.1	0.1	0.1	0.1	228	222	262	254	54	32	0.7	0.8
Idle	9/26,27/67	69	11,495	0.2	0.3	0.1	0.1	0.1	0.2	278	305	314	395	36	90	1.0	1.0
	11/1,2/67	101	18,639	0.2	0.3	0.1	0.05	0.1	0.25	273	293	301	432	28	61	1.0	1.0
IIIa	8/23,24/67	39	6,277	1.8	2.05	0.9	0.4	0.95	1.65	520	509	492	418	28	91	4.35	4.35
30 mph	9/26,27/67	69	11,495	1.6	1.85	0.75	0.35	0.85	1.55	496	493	453	432	43	61	4.3	4.2
40 hp	11/1,2/67	101	18,639	1.6	1.7	0.8	0.3	0.80	1.5	471	456	420	408	51	60	4.3	4.2

---

*Total as ppm formaldehyde.

†Adjusting factor is computed by dividing 15 by the percent (CO and CO_2) in the exhaust using "as-measured" average CO and CO_2 measurements.

Shown on Table 27 of the text is a summary of the statistical analyses which identified instances in which an emission was different. Except for the difference shown during the 20-mph cruise (initial) aldehyde and interim SO_2 measurements, the U_s analysis identified no other instances of statistical difference during the initial and interim evaluations. The final evaluation at 20 mph, however, indicated that CO, acrolein, aldehydes, formaldehyde, NO_x, and SO_2 were statistically different. The CO may be discounted due to the minor difference at 25 ppm. Acrolein,

TABLE 27. EXHAUST EMISSIONS U_s STATISTICAL ANALYSIS SUMMARY
CATALYTIC MUFFLER CODE "X"-3 VS STOCK MUFFLER

Vehicle: Bus 768
Fuel: EM-3A-F

Operating Conditions: See Tables 10 & 14 in Appendix E

Operating Conditions	Test Date	Test Days	Test Miles	Muffler Installed	Average "As-Measured Exhaust Emissions CO, ppm	CO$_2$, percent	Acrolein, ppm	Aldehydes, ppm Form.	Formaldehyde, ppm	NO$_x$, ppm	SO$_2$, ppm
I	8/22/67	39	6,277	"X"-3	*	*	*	21.05	*	*	*
20 mph	8/25/67			Stock				30.0			
40 hp	U_s Statistic							0			
	9/25/67	69	11,495	"X"-3	*	*	*	*	*	*	0.34
	9/28/67			Stock							1.23
	U_s Statistic										0
	10/31/67	101	18,639	"X"-3	150	*	1.15	14.8	3.92	754	0.28
	11/3/67			Stock	125		0.90	12.4	2.52	820	0.90
	U_s Statistic				2		0.5	1.5	0	1	0
II	8/22/67	39	6,277	"X"-3	*	*	1.56	15.2	*	*	*
40 mph	8/25/67			Stock			1.06	24.2			
40 hp	U_s Statistic						0	0			
	9/25/67	69	11,495	"X"-3	90	*	*	6.61	3.2	*	0.32
	9/28/67			Stock	70			10.5	6.3		1.24
	U_s Statistic				0			0	0		0
	10/31/67	101	18,639	"X"-3	65	*	0.90	*	3.39	*	0.25
	11/3/67			Stock	60		0.48		1.98		0.97
	U_s Statistic				2		0		1.5		0
III	8/22/67	39	6,277	"X"-3	115	*	*	14.05	*	232	*
Idle	8/25/67			Stock	90			21.2		211	
	U_s Statistic				1.5			0		0	
	9/25/67	69	11,495	"X"-3	95	*	*	8.60	*	*	0.18
	9/28/67			Stock	80			10.8			0.54
	U_s Statistic				0.5			0			0
	10/31/67	101	18,639	"X"-3	*	*	*	*	*	*	0.17
	11/3/67			Stock							0.36
	U_s Statistic										0

*U_s statistic greater than 2, no statistical difference apparent.

aldehydes and formaldehyde all showed a slight increase in concentration for the "X"-3 muffler. Except for the formaldehyde difference, these increases may be adjudged as slight and not particularly significant. The 66-ppm reduction in NO_x from 820 to 754 does not seem to be particularly significant. An interesting and unexplained trend apparent during the interim and final 20-mph evaluations was the reduced SO_2. For the 40-mph cruise emissions, a statistical difference was indicated during the initial evaluation for both acrolein and aldehydes. Of these two, the aldehyde reduction from 24.2 to 15.2 ppm appeared consistent with the reduction shown for the initial 20-mph evaluation. This same trend continued during the interim evaluation at 40 mph and was also noted during both the initial and interim idle condition for certain acrolein, formaldehyde and CO values. The SO_2 values were identified as different during the interim and final 40-mph cruise and resulted in substantial decreases in measured concentration for the "X"-3 muffler. This trend of SO_2 reduction was also apparent during the interim and final evaluations at 40 mph. In summary of the exhaust emissions measurements obtained with the "X"-3 muffler, generally consistent reductions were found for aldehydes and SO_2. The most consistent reduction appeared in SO_2 during the interim and final evaluations under all operating conditions explored. The detailed statistical analyses are to be found on Tables 64, 72 and 80 of Appendix E.

Shown on the lower half of Table 26 are the average muffler pressures and temperatures obtained concurrently with the odor ratings. Basically, the same comments may be made regarding these measurements as was made for the pressure and temperature measurements obtained for Buses 681 and 678. Catalytic muffler "X"-3 appeared to have little effect on the inlet pressures relative to those obtained with the stock muffler. The measured outlet pressure, however, were different during the 20-, 40-, and 30-mph cruise operating conditions. These outlet pressures varied from about one-third to one-half of those measured with the stock muffler installed. This difference in stock versus "X"-3 outlet pressures was also shown by the differential pressure measurements which indicated a greater pressure drop across "X"-3. Under condition I, the

20-mph cruise, the pressure drop appeared to be about twice that with the stock muffler. Under operating condition II, the 40-mph cruise, and condition IIIa, the 30-mph cruise, the pressure drop with "X"-3 was slightly less than two times that with the stock muffler. The inlet pressure measured at 40 mph during the interim and final evaluations was near the full load specification at 1800 rpm of 3.3 in. Hg. Since the 40-mph, 40-hp condition represents approximately 1650 rpm and about two-thirds power, it may be that this muffler could be considered at the limit of the vehicle back-pressure specification.

The inlet temperatures for "X"-3 were about the same as those for the stock muffler. The outlet temperatures, however, showed the "X"-3 muffler dissipated more of the heat in the exhaust gas than did the stock muffler. The differential temperature for the idle represented a temperature increase due to the heat storage capacity of the 40 lb of catalytic coated 1/4-in. ceramic pebbles. Also listed on the bottom half of Table 26 are the air box pressures measured during the four constant speed conditions. These pressures were approximately the same for the stock and the "X"-3 muffler. Pressures and temperatures were averaged from measurements obtained during the initial, interim, and final inspections, contained on Tables 65, 73 and 81 of Appendix E. Please refer to these tables for exhaust emissions measurements, as well as air box pressures obtained under no load engine operating speeds of 1200, 1800 and 2100 rpm.

4. Summary of Code "X" Muffler Evaluation

In summary of the three performance evaluations conducted with Bus 681, equipped with catalytic muffler "X"-1, only under certain instances did there appear to be a reduction in the odor and other emissions. Muffler "X"-1 had little or no effect on smoke emissions. The greatest effect was during engine idle and acceleration after idle conditions. Odor evaluations during the 20- and 40-mph cruises and generally under the deceleration condition indicated mixed results in that sometimes there appeared to be an improvement, sometimes the change was negligible, and, on a few instances, the odor quality and intensity appeared greater with the catalytic muffler. Only a few of the exhaust emissions measured indicated a significant improvement. The most important difference seemed to be in the areas of partially oxygenated constituents such as total aldehydes, formaldehyde and sometimes acrolein. The reason for slight increases in carbon monoxide and oxides of nitrogen determined under some of the operating conditions has not been resolved. Finally, the operation of the catalytic muffler and the consequent temperatures and pressures appeared to be normal and within expected or specified levels.

The two evaluations conducted with Bus 678 equipped with muffler "X"-2 resulted in improvements during instances. Muffler "X"-2 had little or no noticeable effect on visible smoke emissions for the acceleration after idle. From the statistical analysis, bar charts, and odor data presented, the catalytic muffler resulted in consistent reduced odor during the idle-acceleration and deceleration conditions. The catalytic muffler seemed to be effective in reducing the exhaust odor during the idle condition as measured during the final evaluation but was not apparently effective during the initial evaluation. Odor was consistently higher in intensity during the 20-mph cruise. The consistent reductions in acrolein with "X"-2 represented an example of what may be deemed a significant improvement during the idle condition. Other notable exhaust emissions reductions were the initial acrolein reduction at 20-mph cruise and slight reduction at 40-mph cruise. The catalytic muffler, however, appeared largely ineffective in reducing the formaldehyde concentrations in the exhaust, as well as the total aliphatic aldehydes. The measured muffler pressures and temperatures appeared reasonable and representative.

During the three evaluations of "X"-3 in Bus 768, the catalytic muffler appeared to reduce odor under the idle and idle-acceleration conditions, although the results were not consistent. These reductions in odor intensity were statistically different only for "D, " during the interim idle and idle-acceleration evaluation. Effectiveness of the catalytic muffler on smoke was found only during the final evaluation, particularly during the constant speed, open-rack operation. As far as exhaust emissions were concerned, the catalytic muffler appeared generally effective in reducing sulfur dioxide but only moderately effective and consistent in the reduction of aldehydes. There appeared to be a higher pressure drop across the catalytic muffler during the high speed, high exhaust gas flow operating conditions of 30 and 40 mph relative to the stock muffler.

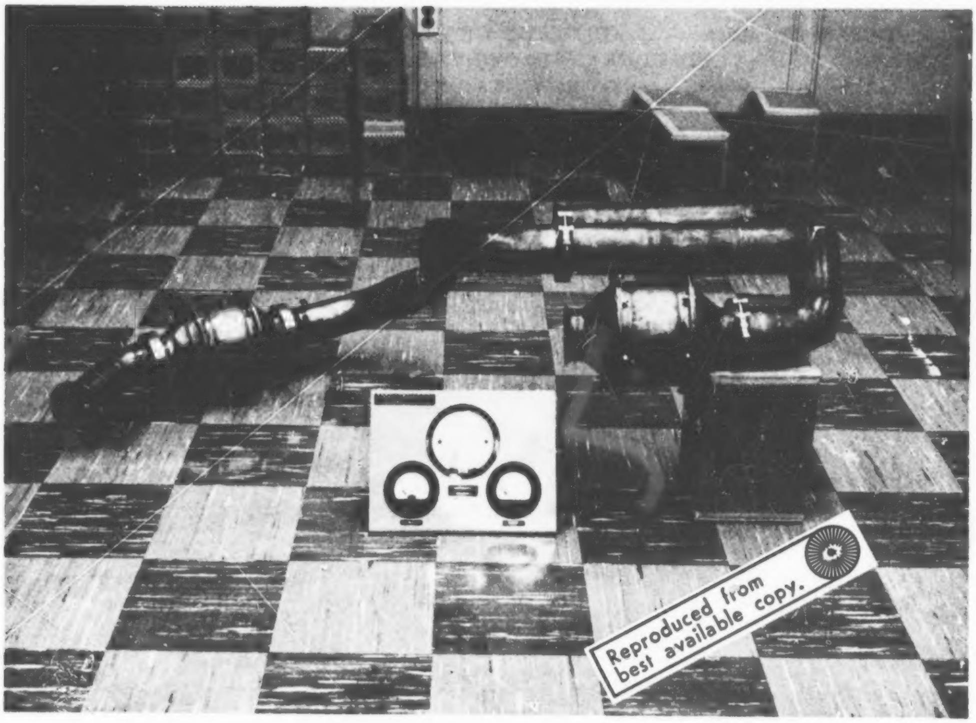
Overall, the three Code "X" catalytic mufflers were subjected to a total of 274 test days and 43, 993 test miles of routine urban-suburban municipal bus operation by the San Antonio Transit System. During a period of approximately 4 months, the Code "X" mufflers were evaluated on eight occasions for their effectiveness in reducing odor, smoke and other selected exhaust emissions. Also measured were operating data such as muffler inlet and outlet pressures and temperatures as well as general engine performance. As a result, the Code "X" catalytic muffler was found to be effective in changing or reducing the vehicle exhaust odor under some conditions and during some inspections. It is felt that an emission reduction device, technique, or system should exhibit consistent effectiveness under most, if not all, operating conditions selected as typical of production of significant levels of odor and smoke. The Code "X" mufflers were found to exhibit odor reductions under basically idle and idle-acceleration type operation. Although the "X"-1 and "X"-3 mufflers had the greatest effect on odor under these conditions, "X"-2 appeared effective only under the idle-acceleration condition. These conclusions should be considered as generalizations due to the sometimes inconsistent results obtained. Generally, mixed results in which a slight reduction, increase, or no change in odor were found under the constant speed 20- and 40-mph conditions and during the deceleration condition.

The three similar Code "X" mufflers had little noticeable effect on vehicle exhaust smoke except for the final evaluation conducted with "X"-3. Only a few of the other exhaust emissions measured were adjudged to be significantly different with the catalytic muffler. For "X"-1, the partially oxygenated constituents such as total aldehydes and formaldehyde seemed to be the most important. For "X"-2, the acrolein emission appeared to have the greatest statistically justified reduction, but these were at the 20- and 40-mph cruise conditions, the same conditions under which the odor results indicated little or no difference. For "X"-3, the muffler appeared effective mainly in reducing sulfur dioxide and moderately effective in the reduction of aldehydes. With regard to the inlet and outlet temperatures and pressures, and other physical performance, the operation of the catalytic Code "X" muffler was within expected or specified levels. Only during the 30- and 40-mph cruise conditions, for the bus equipped with "X"-3, was a substantial increase in pressure drop noted. The results of this screening evaluation should be considered from the standpoint of cost effectiveness to establish the desirability of this type of equipment for diesel odor and emission control. This cost effectiveness study will require fleet evaluation type information on catalyst cost and replenishment, along with installation costs, maintenance costs, and other incidental operating costs which may be attributed to the use of this equipment instead of the standard mufflers.

B. Code "Y" Catalytic Muffler System Evaluation

Covered in this section are the results and data analysis for the experiments conducted with the Code "Y" catalytic exhaust muffler. Shown in Figure 28 is the SwRI designated Code "Y" exhaust catalytic system for use with the GM model TDH 4519 bus powered by the 6V-71 engine. The Code "Y" system consisted of two small cylindrical reactors, 6-1/2-in. diameter by 6-3/8-in. long, fitted with suitable increasing and reducing components to flange connect with the usual 3-in. OD exhaust pipe. The exhaust piping system was modified to permit the location of each reactor as near as possible to each exhaust manifold of the Detroit Diesel 6V-71 engine. One reactor was located adjacent to the right (rear) back of the engine and the other reactor was located in the space normally occupied by the muffler and served the left (front) bank of the engine. The interior of the 6-1/2-in. diameter by 6-3/8-in. long cylindrical reactor was filled with a thin gauge material of honeycomb construction, installed so that the exhaust gases could pass straight through the honeycomb passages with minimal restriction. This thin honeycomb material was apparently intended to provide maximum surface area with a minimum pressure drop. They were located as near to the exhaust manifolds of the engine as possible to preserve and utilize the heat of the exhaust gases. The exact material of construction and catalyst is not known to Southwest Research Institute and is considered a proprietary item.

Initial plans required the operation of the "Y" muffler in a municipal bus powered by a Detroit Diesel 6V-71 E type, two-cycle engine. The plan was to operate the "Y" muffler for a minimum period of 30 days under routine fleet operation by the San Antonio Transit System. After this 30-day initial seasoning period, the bus would be brought into the Vehicle Emissions Laboratory and odor, smoke, and selected emissions measurements obtained on a "back-to-back" basis for the vehicle with the catalytic and then with the standard muffler installed. The plan was then to operate with the "Y" muffler for an additional 30 days and reevaluate the emissions.



Reproduced from best available copy.

FIGURE 28. CATALYTIC DEVICE CODE "Y" EXHAUST SYSTEM

On August 18, 1967, the Code "Y" muffler was installed on Bus 678. This bus, described in detail on Table 1 of Appendix E, had completed 2 months of routine operation with "X"-2. After 17 test days, and 1979 test miles, the fleet test of Bus 678 equipped with the Code "Y" muffler was terminated at the request of the San Antonio Transit System due to an excessive sound level. As soon as the "Y" reactor units were installed on Bus 678, it was known that the sound level from the vehicle was greater than that with the stock muffler. The San Antonio Transit System, however, consented to operate this bus as long as possible at the increased sound level. The mileage accumulation in routine city operation had to be terminated, however, on September 4, 1967, as a result of numerous complaints, first to the San Antonio Transit System and then to the San Antonio Police Department. During the period of operation, a number of different routes were used in an attempt to complete the 30 days of operation. The threat of traffic citations to the Transit System bus drivers, however, ended the road portion of the test after 17 test days. On September 4, the cognizant technical representative of the catalytic muffler manufacturer and the Project Officer were advised.

As a result of the early termination, only one back-to-back evaluation of the "Y" unit was obtained with Bus 678. To further explore the potentiality of the "Y" muffler, it was agreed with the Project Officer to conduct an additional inspection with the "Y" unit installed on one of the other vehicles. The vehicle selected was Bus 768, an identical vehicle to Bus 678 with the exception that the vehicle was newer and powered by a Detroit Diesel 6V-71N. Exactly the same operating conditions, procedures, and measurement methods were employed during the evaluation of the "Y" device as with the Code "X" mufflers and are described on Tables 2 through 6 of Appendix E.

1. Catalytic Reactor System Code "Y" Results

A complete log of tests performed with the "Y" muffler including dates, test days, test mileages, and vehicle/engine maintenance notes may be found on Table 82 in Appendix E. Please refer to this table for a summary of the events and actions taken during the test and evaluation of the Code "Y" muffler in Buses 678 and 768. Shown on Table 28 of this report is an

TABLE 28. OVERALL SUMMARY OF ODOR EVALUATIONS CATALYTIC MUFFLER CODE "Y" VS STOCK MUFFLER

Vehicle: Buses 678 & 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Bus No.	Test Date	Test Days	Test Miles	Muffler	"D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I 20 mph 40 hp	678	9/7/67	17	1979	Stock	6.3	2.0	1.8	1.4	1.2
		9/6/67	17	1979	"Y"	5.2	1.4	1.2	0.9	1.2
					Net Change	-1.1	-0.6	-0.6	-0.5	0
	768	11/8/67	17	1979	Stock	4.9	1.3	1.0	0.8	0.5
		11/7/67	17	1979	"Y"	5.1	1.2	0.6	0.3	1.7
					Net Change	+0.2	-0.1	-0.4	-0.5	+1.2
II 40 mph 40 hp	678	9/7/67	17	1979	Stock	6.3	2.0	1.6	1.2	1.2
		9/6/67	17	1979	"Y"	4.8	1.5	1.4	0.7	0.8
					Net Change	-1.5	-0.5	-0.4	-0.5	-0.4
	768	11/8/67	17	1979	Stock	4.7	1.3	0.9	0.7	0.8
		11/7/67	17	1979	"Y"	4.5	0.8	0.8	0.5	1.0
					Net Change	-0.2	-0.5	-0.1	-0.2	+0.2
III Idle	678	9/7/67	17	1979	Stock	5.9	1.7	1.5	1.3	1.2
		9/6/67	17	1979	"Y"	4.8	1.3	1.3	0.8	0.8
					Net Change	-1.1	-0.4	-0.2	-0.5	-0.4
	768	11/8/67	17	1979	Stock	5.5	1.5	1.1	0.9	0.8
		11/7/67	17	1979	"Y"	4.3	1.1	0.8	0.8	0.5
					Net Change	-1.2	-0.4	-0.3	-0.1	-0.3
IV Idle-Acceleration	678	9/7/67	17	1979	Stock	5.7	1.9	1.6	1.0	1.2
		9/6/67	17	1979	"Y"	6.3	1.9	1.7	1.0	1.5
					Net Change	+0.6	0	+0.1	0	+0.3
	768	11/8/67	17	1979	Stock	6.8	2.0	1.9	1.1	1.0
		11/7/67			"Y"	5.8	2.0	1.3	0.9	1.1
					Net Change	-1.0	0	-0.6	-0.2	+0.1
V Deceleration	678	9/7/67	17	1979	Stock	6.3	2.0	1.6	1.3	1.5
		9/6/67	17	1979	"Y"	4.8	1.4	1.2	0.8	0.8
					Net Change	-1.5	-0.6	-0.4	-0.5	-0.7
	768	11/8/56	17	1979	Stock	4.0	1.1	0.8	0.6	0.4
		11/7/67	17	1979	"Y"	3.3	1.0	0.7	0.3	0.1
					Net Change	-0.7	-0.1	-0.1	-0.3	-0.3

overall summary of the odor evaluations with "Y" evaluated back-to-back with the standard muffler. The muffler was successful in reducing the panel rating under most conditions and instances evaluated. Although there were a few increases in odor quality and intensity noted, these appeared to be marginal or slight and, overall, were outweighed by the positive reduction generally noted. The few instances which resulted in little or no change appeared to be most prevalent for Bus 768 powered by the N type engine. A graphic representation of the data summarized on Table 28 is presented in Figures 29 and 30. Because of the excessive sound level, the test days and test miles accumulated on "Y" were the same for both evaluations.

The Figure 29 bar graph, for Bus 678 after 17 test days and 1979 test miles, indicates that only under the idle-acceleration, condition IV, did "Y" not have a beneficial effect. According to Figure 30 for the same "Y" muffler but installed on Bus 768, the device appeared to be effective under all conditions except the 20-mph cruise, condition I. The greatest effect appeared under the idle, condition III.

Shown on Tables 83 and 91 of Appendix E are comparisons of odor panel responses for Buses 678 and 768, made on September 6 and 7 and November 7 and 8, 1967, respectively. These two comparison tables were used to prepare the Table 28 summary in the text. Tables 84 and 84A-84E and 85 and 85A-85E list in detail Bus 678 odor panel responses and their distribution. The same supporting information may be found in Appendix E, Tables 92 and 92A-92E and 93 and 93A-93E for the other evaluations made with Bus 768. The response distribution and the variability indicated by these support tables for Buses 678 and 768 appear similar to previous studies.

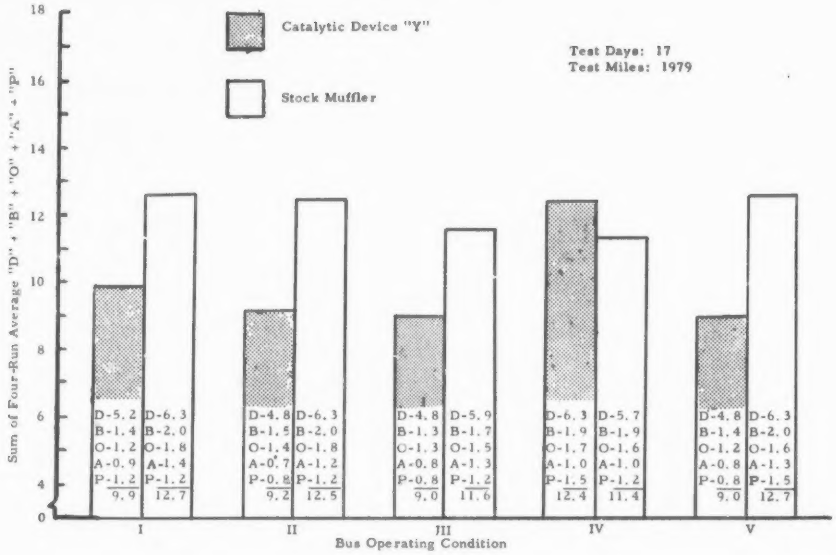


FIGURE 29. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 678, Date: September 6 and 7, 1967)

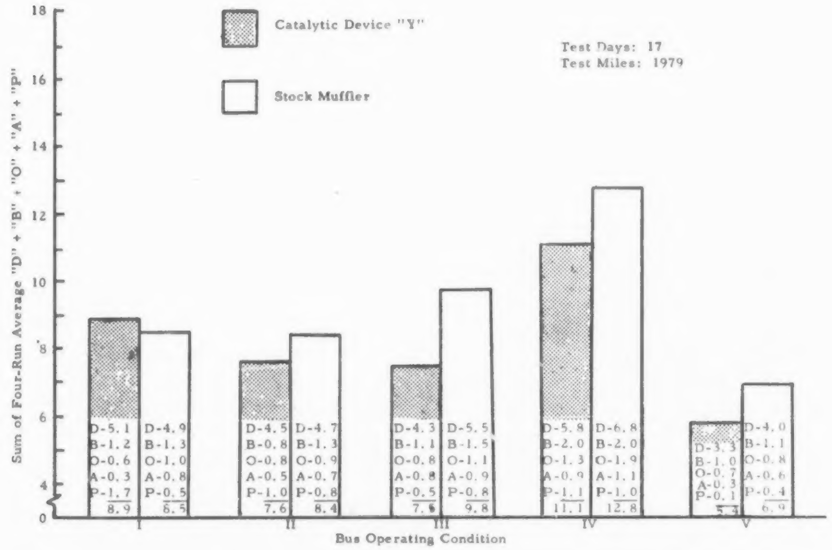


FIGURE 30. OVERALL COMPARISON OF DIESEL ODOR EVALUATION WITH AND WITHOUT CATALYTIC MUFFLER INSTALLED

(Bus 768, Date: November 7 and 8, 1967)

The "U_s" statistical analysis applied to the odor data are summarized on Table 29 in the text. More times than not, a statistical difference was found, particularly the "D" ratings. Table 29 also reveals the "Y" muffler had a more consistent effect on odor with Bus 678 than with Bus 768. Under conditions I and II, the 20- and 40-mph cruises, the odor responses for "D," "B," "O," and "A" with vehicle 678 equipped with the "Y" muffler were always statistically different and less than with the stock muffler. Under these same two conditions, "Y" equipped Bus 768 showed only a minor change in odor quality and intensity, even though it was in favor of the "Y" unit. Under the idle, condition III, "Y" appeared equally effective in reducing odor qualities of "D," "B," and "P." The almost identical net changes in these three qualities, identified as statistically different, were perceived by the SwRI panel, even though 2 months lapsed between tests, and the tests were with buses powered by slightly different, two-cycle engines.

The results of idle-acceleration evaluation, condition IV, indicated that the stock muffler produced slightly less odor than Bus 678 equipped with "Y," while the reverse was true for Bus 768. This was the only condition in which the "Y" muffler failed to demonstrate a positive reduction in perceived odor (Bus 678). The statistically different Q/I ratings under deceleration, condition V, indicated the significant effect the "Y" muffler had on odor from Bus 678. The reduction in "D" rating of 1.5 is close to the "D"-1.6 rating difference under condition I and identical to the "D"-1.5 found under condition III for Bus 678. Considering the "B," "O," and "A" ratings for the same three operating conditions in Bus 678, the net changes were surprisingly consistent, averaging a net reduction of "B"-0.6, "O"-0.5, and "A"-0.5. The statistics also revealed the "Y" muffler in Bus 768 was apparently effective in changing the "D," "A," and "P" ratings downward. For further study of the data listed on Table 29, please refer to Tables 86 and 94 of Appendix E. In summary, the bar charts on Figures 29 and 30 depict the relative effectiveness of the "Y" catalytic muffler in light of the statistical analysis. The differences shown in Figure 29 for all five conditions are identified in Table 29 as being statistically different. A statistical difference was also found for all

TABLE 29. ODOR RESPONSE U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "Y" VS STOCK MUFFLER

Vehicle: Buses 678 & 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions: See Tables 2 through 6 in Appendix E

Operating Conditions	Test Vehicle	Test Date	Test Days	Test Miles	Muffler	Average Odor Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I 20 mph 40 hp	Bus 678	9/5/67	17	1979	"Y"	5.2	1.4	1.2	0.9	
		9/8/67			Stock	6.8	2.0	1.8	1.4	
		U_s Statistic				2	0	0.5	0	*
	Bus 768	11/6/67	17	1979	"Y"			0.6	0.3	1.7
		11/9/67			Stock			1.0	0.8	0.5
		U_s Statistic				*	*	0	0	0
II 40 mph 40 hp	Bus 678	9/5/67	17	1979	"Y"	4.8	1.5	1.4	0.7	
		9/8/67			Stock	6.3	2.0	1.8	1.2	
		U_s Statistic				0	0.5	0.5	1	*
	Bus 768	11/6/67	17	1979	"Y"	4.5				
		11/9/67			Stock	4.7				
		U_s Statistic				1.5	*	*	*	*
III Idle	Bus 678	9/5/67	17	1979	"Y"	4.8	1.3		0.8	0.8
		9/8/67			Stock	5.9	1.7		1.3	1.2
		U_s Statistic				2	1	*	0	1
	Bus 768	11/6/67	17	1979	"Y"	4.3	1.1			0.5
		11/9/67			Stock	5.5	1.5			0.8
		U_s Statistic				0	0	*	*	2
IV Idle- Acceleration	Bus 678	9/5/67	17	1979	"Y"	6.3				1.5
		9/8/67			Stock	5.7				1.2
		U_s Statistic				1	*	*	*	0.5
	Bus 768	11/6/67	17	1979	"Y"	5.8	2.0	1.3		
		11/9/67			Stock	6.8	2.0	1.9		
		U_s Statistic				0	0.5	0	*	*
V Idle Deceleration	Bus 678	9/5/67	17	1979	"Y"	4.8	1.4	1.2	0.8	0.8
		9/8/67			Stock	6.3	2.0	1.6	1.3	1.5
		U_s Statistic				0	0	0	0	0
	Bus 768	11/6/67	17	1979	"Y"	3.3			0.3	0.1
		11/9/67			Stock	4.0			0.6	0.4
		U_s Statistic				0	*	*	0	0.5

---

*U_s statistic greater than 2, no statistical difference apparent.

Bus 768 conditions except condition I. These fairly consistent reductions under four out of five operating conditions point to the relative effectiveness of the Code "Y" muffler on diesel exhaust odor.

Shown on Table 30 of the text is an overall summary of the smoke evaluations conducted under both steady state and transient conditions. Listed are the test days and test miles, average smoke readings and the smoke reduction in percent opacity. From a review of the constant speed results, the effect of "Y" on smoke was negligible and in most instances resulted in an increase in smoke reading. This was particularly evident for Bus 678. A review of the idle-acceleration smoke readings listed on Table 30 indicates no reduction in smoke with the "Y" muffler. In fact, the smoke readings increased up to 4.7-percent opacity from 9 to 13.7 percent for the "Y" equipped Bus 678. The smoke results summarized on Table 30 are included in Tables 87 and 95 of Appendix E.

TABLE 30. OVERALL SUMMARY OF SMOKE EVALUATIONS
CATALYTIC MUFFLER CODE "Y" VS STOCK MUFFLER

Vehicle: Buses 678 & 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions: See Tables 7 through 9 in Appendix E

Dates Evaluated: See below

Constant Speed (All open rack - maximum power output)

Operating Conditions	Bus No.	Vehicle Speed, mph	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, % Opacity
						Stock	"Y"	
A	678	20	9/6,7/67	17	1979	16.3	20.0	(3.7)*
	768		11/6,8/67	17	1979	13.7	16.0	(2.3)
B	678	25	9/6,7/67	17	1979	13.3	16.0	(2.7)
	768		11/6,8/67	17	1979	9.0	8.7	0.3
C	678	30	9/6,7/67	17	1979	12.0	14.7	(2.7)
	768		11/6,8/67	17	1979	8.3	7.0	1.3
D	678	35	9/6,7/67	17	1979	9.2	11.3	(2.1)
	768		11/6,8/67	17	1979	5.3	5.3	0

Idle-Acceleration (40 hp at 30 mph preset and retained)

Portion of "E" Idle-Acceleration	Bus No.	Test Date	Test Days	Test Miles	Average PHS Smoke Reading, Percent Opacity		Smoke Reduction, % Opacity
					Stock	"Y"	
Engine Start	678	9/6,7/67	17	1979	13.3	20.0	(6.7)
	768	11/6,8/67	17	1979	1.0	2.7	(1.7)
During Acceleration	678	9/6,7/67	17	1979	9.0	13.7	(4.7)
	768	11/6,8/67	17	1979	8.3	8.7	(0.4)
After Upshift	678	9/6,7/67	17	1979	11.0	13.0	(2.0)
	768	11/6,8/67	17	1979	10.0	8.0	2.0

---

*( ) indicates increase in smoke with catalytic muffler installed

Summarized on Table 31 of the text are the average "as-measured" exhaust emissions and muffler pressure and temperature measurements obtained for the "Y" muffler. The effect of the catalytic muffler on CO production was notable. Under conditions I and II, the 20- and 40-mph cruises, CO concentrations in the exhaust were consistently lower for the "Y" equipped vehicles. The effect of "Y" on CO under the idle, condition III, was negligible for both Buses 678 and 768. The "Y" muffler appeared to affect the CO_2 concentration, but this effect was slight. Acrolein, aliphatic aldehydes, and formaldehyde were largely affected by the "Y" muffler in Bus 678.

TABLE 31. SUMMARY OF AVERAGE "AS-MEASURED" EXHAUST EMISSIONS AND MUFFLER PRESSURE AND TEMPERATURE MEASUREMENTS CATALYTIC MUFFLER CODE "Y" VS STOCK MUFFLER

Vehicle: Buses 678 & 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions:
Exhaust Emissions: See Table 10
Muffler Pressure and Temperature: See Table 11 & 12

Average "As-Measured" Exhaust Emissions

Operating Condition	Test Vehicle	Test Date	Test Days	Test Miles	CO, ppm		CO2, %		Acrolein, ppm		Aliphatic Aldehydes*, ppm		Formaldehyde, ppm		NOx, NO2, ppm		SO2, ppm		Adjusting Factor†	
					Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"
I 20 mph 40 hp	Bus 678	9/5, 8/67	17	1979	200	140	5.8	5.7	8.8	1.33	44.3	9.3	25.9	7.3	655	566	0.92	1.22	2.58	2.62
	Bus 768	11/6, 9/67	17	1979	150	55	4.55	4.5	0.83	0.86	8.45	12.95	4.32	3.6	765	773	1.08	0.22	3.29	3.33
II 40 mph 40 hp	Bus 678	9/5, 8/67	17	1979	125	75	4.1	3.95	3.35	0.62	30.4	8.2	19.0	5.4	402	378	0.85	1.13	3.65	3.80
	Bus 768	11/6, 9/67	17	1979	70	45	3.65	3.50	0.55	0.43	9.7	12.75	3.6	3.08	479	528	1.19	0.38	4.11	4.29
III Idle	Bus 678	9/5, 8/67	17	1979	190	205	1.1	1.25	6.1	2.22	38.7	18.4	22.1	16.1	116	136	0.14	0.42	13.4	11.8
	Bus 768	11/6, 9/67	17	1979	90	80	1.25	1.20	0.62	0.77	10.65	13.65	4.22	4.50	246	266	0.55	0.23	12.0	12.5

Average Muffler Pressure and Temperature Measurements

Operating Conditions	Test Vehicle	Test Date	Test Days	Test Miles	Muffler Pressure, in. Hg						Muffler Temperature, °F						Air Box Pressure, in. Hg	
					Inlet		Outlet		Differential		Inlet		Outlet		Differential			
					Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"	Stock	"Y"
I 20 mph 40 hp	Bus 678	9/6, 7/67	17	1979	1.1	1.75	0.4	0.9	0.7	0.8	586	690	496	675	90	15	1.65	2.0
	Bus 768	11/7, 8/67	17	1979	0.7	1.1	0.4	0.6	0.3	0.5	461	502	390	442	71	60	1.1	2.0
II 40 mph 40 hp	Bus 678	9/6, 7/67	17	1979	3.7	4.6	1.25	3.1	2.4	1.55	592	624	548	620	44	4	8.1	8.9
	Bus 768	11/7, 8/67	17	1979	2.6	3.4	1.3	2.6	1.4	0.8	507	536	467	507	40	27	7.2	7.0
III Idle	Bus 678	9/6, 7/67	17	1979	0.25	0.35	0.10	0.20	0.15	0.20	295	293	347	336	52	43	0.75	0.80
	Bus 768	11/7, 8/67	17	1979	0.3	0.3	0.2	3.2	0.1	0.1	272	286	319	321	47	35	1.1	1.7
IIIa 30 mph 40 hp	Bus 678	9/6, 7/67	17	1979	1.9	2.7	0.55	1.80	1.40	1.0	551	593	485	586	66	7	4.25	4.8
	Bus 768	11/7, 8/67	17	1979	1.4	2.0	0.6	1.6	0.7	1.4	459	488	409	455	50	33	3.3	4.0

---

*Total as ppm formaldehyde.

†Adjusting factor is computed by dividing 15 by the percent (CO and CO2) in the exhaust using "as-measured" average CO and CO2 measurements.

Occasionally, changes in these three constituents were noted for Bus 768. For Bus 678, the acrolein values were significantly reduced from 8.8 to 1.33 ppm at the 20-mph cruise, from 3.35 to 0.62 ppm during the 40-mph cruise, and from 6.1 to 2.22 ppm during the idle. On the other hand, acrolein concentrations in the exhaust from Bus 768 (adjudged low with the stock muffler) were essentially unchanged by "Y."

Total aliphatic aldehydes likewise were significantly reduced with the "Y" muffler in Bus 678. For example, the 20-mph cruise total aldehydes were reduced from 44.3 to 9.3 ppm. The 40-mph cruise aldehydes were reduced from 30.4 to 8.2 ppm, and idle aldehydes were reduced from 38.7 to 18.4 ppm. For Bus 768, however, it appeared the aldehydes were increased slightly under all three conditions from an overall average of 9.5 ppm to about 13 ppm. Sizeable reductions in formaldehyde were also noticed when Bus 678 was operated with the Code "Y" muffler. During condition I, the stock formaldehyde reading of 25.9 was reduced to 7.3 ppm. During condition II, "Y" was able to reduce the stock 19.0-ppm level to 5.4 ppm, and, during the idle condition, the formaldehyde was reduced from 22.1 to 16.1 ppm. Slight reductions in formaldehyde were noticed when the "Y" muffler was installed on Bus 768 except during the idle condition when a small increase in formaldehyde was noted. The "Y" muffler did not have a drastic effect on NO_x except during the 20-mph condition with Bus 678 in which the stock concentration was reduced from 655- to 566-ppm NO_2 and during operating condition II with Bus 768 when the concentration increased from 479- to 528-ppm NO_2. Slight increases were noted during the idle condition for the "Y" muffler installed on both Buses 678 and 768. The reduction in NO_x during condition I with Bus 678 is difficult to explain, although the slight increases in NO_x can be justified. The SO_2 values for Bus 678 appeared to increase slightly under all conditions. The reverse was true for Bus 768 in which SO_2 appeared to be greatly reduced under conditions I and II, and partially reduced under condition III. The final column of Table 31 lists adjusting factors which may be utilized to normalize the average "as-measured" exhaust emissions for the effect of diluent air. Summarized on Table 32 are the results of the statistical analysis of the emission data for each condition for Bus 678 and then Bus 768. Only when the statistical analysis indicated a difference were the values brought forward from the supporting tables in Appendix E and indicated. The 20-mph results for Bus 768 indicated that acrolein, aldehydes, formaldehyde, and NO_x were statistically different. The "Y" acrolein, aldehydes, and formaldehyde concentrations were lower, approximately one-fourth to one-fifth as large as with the stock muffler. Bus 768, 20-mph cruise results showed only aldehydes and formaldehyde as different

TABLE 32. EXHAUST EMISSIONS U_s STATISTICAL ANALYSIS SUMMARY CATALYTIC MUFFLER CODE "Y" VS STOCK MUFFLER

Vehicle: Buses 678 & 768
Fuel: EM-3A-F (No. 1 Diesel)

Operating Conditions: See Tables 10 & 14 in Appendix E

						Average "As-Measured" Exhaust Emissions						
Operating Conditions	Test Vehicle	Test Date	Test Days	Test Miles	Muffler Installed	CO, ppm	CO_2, %	Acrolein, ppm	Aldehyde, ppm	Formaldehyde, ppm	NO_x, ppm	SO_2, ppm
I 20 mph 40 hp	Bus 678	9/5/67	17	1979	"Y"			1.33	9.3	7.3	566	
		9/8/67			Stock			8.8	44.3	25.9	655	
		U_s Statistic				*	*	0	0	0	0	*
	Bus 768	11/6/67	17	1979	"Y"				12.95	3.6		
		11/9/67			Stock				8.45	4.32		
		U_s Statistic				*	*	*	0	0	*	*
II 40 mph 40 hp	Bus 678	9/5/67	17	1979	"Y"	75		0.62	8.2	5.4	378	1.13
		9/8/67			Stock	125		3.35	30.4	19.0	402	0.85
		U_s Statistic				0	*	0	0	0	2	2
	Bus 768	11/6/67	17	1979	"Y"	45					528	0.38
		11/9/67			Stock	70					479	1.39
		U_s Statistic				0	*	*	*	*	0	0
III Idle	Bus 678	9/5/67	17	1979	"Y"	205		2.22	18.4	16.1	136	0.42
		9/8/67			Stock	190		6.10	38.7	22.1	116	0.14
		U_s Statistic				0	*	0	0	0	0	0
	Bus 768	11/6/67	17	1979	"Y"							0.55
		11/9/67			Stock							0.23
		U_s Statistic				*	*	*	*	*	*	0

---

*U_s Statistic greater than 2, no statistical difference apparent.

even though an increase in aldehydes and an almost negligible decrease in formaldehyde were found. During the 40-mph cruise, differences were indicated for CO, acrolein, aldehydes, formaldehyde, NO_x and SO_2 for the "Y" equipped Bus 678. The change in CO is significant. The change in acrolein downward with the catalytic muffler was encouraging and may be considered a gross change. Downward reductions in aldehydes and formaldehyde concentrations may also be considered as gross changes with the "Y" muffler relative to the stock muffler. The statistical difference shown for oxides of nitrogen during the final evaluation is not considered significant. The statistical analysis identified the "Y" muffler to change only three Bus 768 emissions during the 40-mph cruise. CO was reduced from 70 to 45 ppm by the "Y" muffler, a moderate though positive indicator. NO_x was increased from 479 to 528 ppm, a practically negligible increase. The SO_2 reduction from 1.39 to 0.38 ppm was interesting, yet difficult to explain.

Applying the "U_s" test to the emissions results for Bus 678 under the idle condition revealed that a statistical difference was found for all of the emissions measured except CO_2. For Bus 768, however, the reverse was true. The exhaust from Bus 678 continued to be favorably affected as regards acrolein, total aldehydes, and formaldehyde by the "Y" muffler. The statistical differences identified for CO and NO_x represent slight changes that may be neglected. The gross reduction in acrolein and total aldehydes from 6.1 to 2.2 ppm and 38.7 to 18.4 ppm, respectively, does appear significant. As in the case of Bus 768, it is difficult to explain the increase in SO_2 found with the "Y" muffler. In summary, most of the emissions measured for Bus 678 were indicated as statistically different for the "Y" relative to the stock muffler. When the differences are considered in light of the measurement techniques employed, a number of the data points appear to have significance. The emissions which appeared to be favorably and substantially affected by the action of the Code "Y" muffler were the partially oxygenated materials represented by acrolein, total aldehydes and formaldehyde. Contained in Tables 89 and 97 of Appendix E are the statistical analyses for the inspections of Buses 678 and 768 equipped with the "Y" muffler.

Shown on the lower portion of Table 31 in the text is an overall summary of the average muffler pressure and temperature measurements, as well as the engine air box pressure measurements. Pressures and temperatures were obtained at the inlet and outlet of the reactor connected to the left (rear) bank of the engine. The thermocouples were located midway in the gas stream at the same position as the pressure taps. The inlet pressures were not excessive when compared to the maximum backpressure allowable with this type of engine. The backpressures for the "Y" device were greater, however, than those measured with the stock muffler. There appeared to be little significant difference in pressure drop tendencies with either muffler. If anything, "Y" had a slight increase in pressure drop. The inlet temperatures were always higher than the outlet temperatures, resulting in a temperature drop or decrease across the stock and "Y" mufflers. These differential temperatures indicate the temperature drop across the one "Y" reactor was generally less than that for the standard unit. The "Y" temperature differentials were substantially less when the muffler was installed on Bus 678 than Bus 768 even though the mounting arrangement was the same. The engine air box pressures did not appear to be greatly affected by the presence of the catalytic muffler instead of the standard stock unit. This implies that the modified piping and muffler exhaust system did not seriously change the breathing characteristic of either two-cycle engine. Contained on Tables 90 and 98 in Appendix E are summaries of the pressure and temperature measurements obtained with Buses 678 and 768. Also shown on these two tables are the air box pressures obtained under no load. Shown in Figure 31 is a close-up of the two Code "Y" reactors after 17 test days and 1979 test miles on Bus 678. One of the reactor flanges was removed to illustrate the honeycomb structure within the reactor. Although a layer of soft smoke and soot particulate covered the surfaces of the honeycomb passages and the connecting flanges, none appeared to be plugged with carbon.

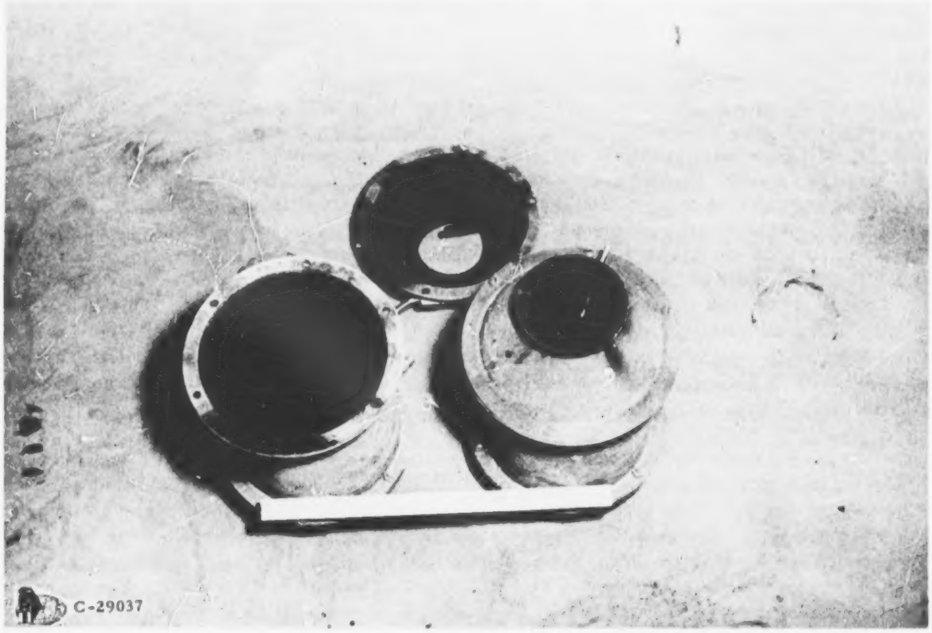


FIGURE 31. CODE "Y" CATALYTIC DIESEL EXHAUST REACTORS

(Removed after 1979 Test Miles and 17 Test Days)

2. Summary

In summary of the two performance evaluations conducted with the Code "Y" muffler in Buses 678 and 768, the "Y" device appeared to reduce odor and certain of the exhaust emissions. The catalytic muffler, however, had no beneficial effect on smoke emissions and, in some instances, resulted in slightly higher smoke readings. Fairly consistent reductions in odor quality and intensity were found under four of the five conditions. These favorable reductions reveal the relative effectiveness of the Code "Y" muffler on diesel exhaust odor. The reductions were found to be greater with Bus 678 compared to the reductions found for the same muffler installed on Bus 768. Consistent reductions were also found in exhaust emissions, such as acrolein, aldehydes and formaldehyde. Gross changes were found with Bus 678, and slight changes were found with Bus 768. The reason for the apparent better performance of the "Y" muffler on Bus 678 versus Bus 768 is not completely understood. It may be the emissions from N powered Bus 768 were lower to begin with and the catalytic device, working from a lower base line, was less efficient. The operation of the catalytic muffler and the consistent temperatures, pressures, and other physical performance information appeared to be normal.

VIII. CHEMISTRY STUDIES

The objective of this portion of the program was twofold: first, to provide chemical support for the catalytic muffler evaluation, and, second, to conduct a preliminary feasibility study of chemical techniques for possible correlation with the human odor panel. Although the two objectives overlapped, they are discussed separately.

A. Exhaust Chemistry

This part involved the familiarization, selection, development, and preparation necessary to sample and analyze various diesel exhaust constituents. The end result was to measure, routinely, exhaust emissions during the evaluation of exhaust catalyst devices, Section VII and to acquire base line data with the Flxible Coach, Section IX. During the initial familiarization with and selection of exhaust constituents for measurement, reviews were made of recent literature including papers and reports pertaining to diesel exhaust chemistry and previous related PHS sponsored programs. In addition, discussions were held, including visits and/or personal contact, with both private and government concerns as to those emissions felt to be of importance and their method of sampling and analysis. The selection was made on the basis that the emission was of overall importance and/or the emission had been shown to correlate somewhat with human judgment and evaluation. With the agreement of the Project Officer, the following list of exhaust constituents was selected for initial consideration:

- Carbon monoxide
- Carbon dioxide
- Unburned hydrocarbons
- Acrolein
- Formaldehyde
- Total aldehydes
- Total carbonyls
- Total unsaturates
- Bicarbonate color
- Oxides of nitrogen
- Sulfur dioxide

On January 26, 1967, chemists representing the Vehicle Emissions Research Laboratory, Southwest Research Institute, and the Petroleum Research Center, U.S. Bureau of Mines, Bartlesville, Oklahoma, visited with the staff of Scott Laboratories in Perkasie, Pennsylvania, to discuss the analytical procedures used during recent exhaust chemistry and odor correlation studies. The purpose of this meeting was to coordinate the odor chemistry effort in each of the three laboratories doing contract research on diesel odor for the Public Health Service. The analytical methods used by Scott are listed briefly as follows:

	Constituent	Method	Reference
(1)	Acrolein	Cohen and Altshuller, 1961, hexylresorcinol method	8, 9
(2)	Total Aldehydes	Sawicki, 1961, MBTH method	10, 11

Constituent	Method	Reference
(3) Bicarbonate Color	Colorimetric, compared to dichromate standard	12
(4) CO and CO_2	Nondispersive infrared (NDIR)	--
(5) Total Unburned Hydrocarbons	High temperature flame ionization analysis	7
(6) Total Carbonyls	Siggia, 1963, 124, dinitrophenyl hydrazine	12, 13
(7) Formaldehyde	Altshuller, et al., 1961, chromotropic acid	12, 14
(8) Nitrogen Oxides	Saltzman, 1954, sulfanilic acid colorimetry and NDUV	15
(9) Total Unsaturates	Siggia, 1963, bromine-potassium bromide method	12, 13
(10) Sulfur Dioxide	West and Gaeke, 1956, disulfitomercurate colorimetric method	16

Not all references describing the above methods are listed, only those particularly helpful in the analysis of vehicle exhaust samples. Due to the lack of a suitable, commercially available, high temperature, direct flame ionization instrument, analysis of the total unburned hydrocarbons was deferred until such time as an appropriate instrument is available. Although gas-liquid chromatography has been used with success by some laboratories, this technique was felt to have some inherent disadvantages. The technique, however, does appear to be useful in determining relative differences.

Many of the previously listed and referenced techniques were generalized procedures requiring experimentation and development, particularly in sampling. In discussions with the staff at Scott Laboratories, it was found that their sample point was 12 in. from the exhaust manifold of the engine, and the sample was obtained by means of a stainless steel probe mounted in the pipe. It was reported that Mylar sample bags were used to transfer the exhaust gas sample from the dynamometer area to the analytical lab. Generally, two samples were taken under each condition, chemically analyzed, and then compared with the odor panel responses. On February 1, 1967, representatives of the Petroleum Research Center visited to observe the odor panel in action, discuss measurement procedures and conditions, and the experience of this laboratory with diesel odor and smoke measurement. Also discussed were the routine type exhaust analyses being considered by the Petroleum Research staff in their odor correlation study. The methods in use at the Petroleum Research Center were discussed and the planned methods for use by Southwest Research Institute were reviewed. Briefly, the reported Petroleum Research Center methods involved generally the same analysis methods as previously listed for the Scott Laboratories, with the exceptions mainly in the sampling and sample transfer. Instead of using bags, it was mentioned that stainless steel surplus oxygen cylinders were used to transfer exhaust samples to the analytical area. Other differences were noted in the method of measurement of oxides of nitrogen. The objectives of the Petroleum Research Center program also required measurement of total hydrocarbons and detailed hydrocarbon analyses by gas liquid chromatography up to C_{20}. Measurements of CO_2, CO, O_2 and H_2 were also reported as part of their program.

As a result of the additional clarification provided by the Project Officer and on the basis of the results from the Fall, 1966, Scott-Katti correlation program, Reference 6, it was agreed to consider in addition to CO, CO_2, and SO_2, the following:

- Acrolein
- Total Aldehydes

- Formaldehyde
- Oxides of nitrogen
- Bicarbonate color

The above list, in order of apparent importance, was determined as a result of the preliminary indications available from the statistical analysis of the Scott correlation between various selected odor constituents and human odor panel quality/intensity evaluations; summarized as follows:

Constituent	Apparent Preliminary Trend
(1) NO_X	High odor intensities accompanied by low NO_X concentrations--converse not true.
(2) Total carbonyls	Total carbonyls showed no useful trend.
(3) Formaldehyde	High formaldehyde values accompanied by high odor intensities--converse not true.
(4) Total aldehydes	High total aldehyde values accompanied by high odor intensities--converse not true.
(5) Bicarbonate color	High bicarbonate color values accompanied by high odor intensities--converse not true.
(6) Unburned fuel	Unburned fuel values showed no useful trend.
(7) CO_2	CO_2 values showed no useful trend.

After consideration of the Scott methods, the planned Petroleum Research analyses, and the objective of this phase, it was decided that the wet chemistry methods for acrolein, formaldehyde, total aldehydes, and bicarbonate color would be employed. Oxides of nitrogen determination would be by means of a modified Saltzman method. The West and Gaeke method for measurement of sulfur dioxide was tentatively selected, and a conventional Beckman 315 NDIR for 0 to 15 percent CO_2 was made available. A similar instrument, modified with longer sample and reference cells, was picked to measure CO in the range of 0 to 2000 ppm. Because of the large number of analyses expected, the emphasis in adaptation of the methods was to minimize the time and detail involved and to maximize the number of determinations. For this reason, and because of the geometry of the Vehicle Emissions Laboratory, it was planned that bag or tank samples would not be obtained, but, rather, samples would be obtained direct from the exhaust pipe. The advantages of direct sampling include, among others, reduced chance of condensation, reaction, loss or change of the exhaust during storage, improved sensitivity because of lack of diluent, and inherent simplicity. The one disadvantage was the inability to sample other than at steady state, constant speed operation. The sample points were located in the laboratory central exhaust stack 6 ft from the exhaust pipe of the vehicle as shown in Figure 3, Section II. Shown in Figure 32 is the sampling and wet collection apparatus located adjacent to the central laboratory exhaust stack (indicated by arrow). An additional view of the sampling train used to obtain exhaust samples with the Flxible Coach is shown in Figure 33 of Section VIII. Two chemical technicians were required to obtain samples for acrolein, oxides of nitrogen, sulfur dioxide, formaldehyde and total aldehydes simultaneously. Not shown is the sample train which included a filter, ice water condenser, glass pump, fiber filter, CO NDIR, CO_2 NDIR, and O_2 polarographic instruments and flowmeter in series. A TI dual pen "Servoriter" was used to obtain continuous traces of the CO/CO_2 emissions.

A partial view of some of the glassware required to analyze the wet collected exhaust samples is shown in Figure 33. Note the rack of tall Nestler tubes against the wall which were prepared as color standards for visual comparison in the bicarbonate color procedure. After repeated attempts to utilize this technique for "odor intensity," it was abandoned. The difficulty found was the large quantity of sample required, about 75 liters. Pilot studies with a single-cylinder GM 1-71 series

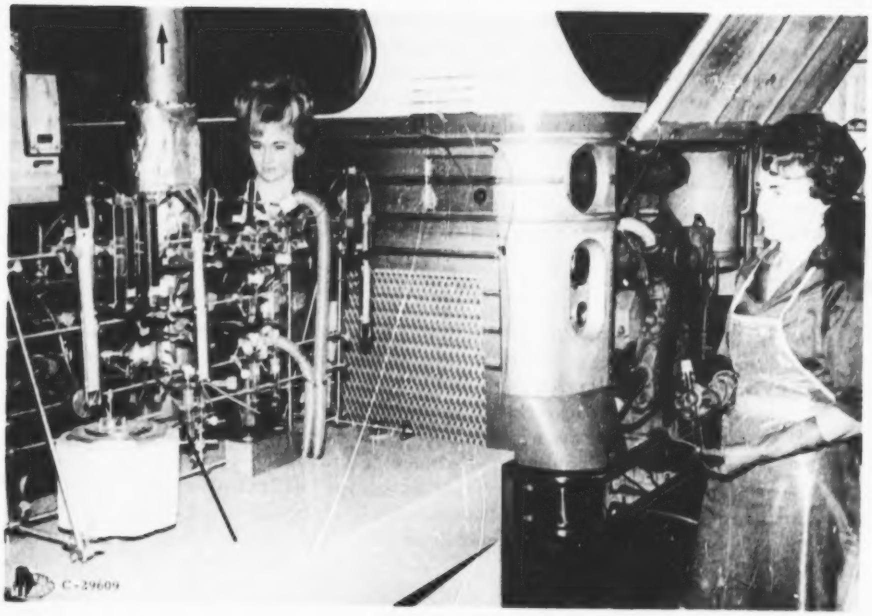


FIGURE 32. SAMPLING AND WET COLLECTION GLASSWARE AND APPARATUS FOR EXHAUST EMISSIONS FROM DIESEL POWERED VEHICLES

Reproduced from best available copy.

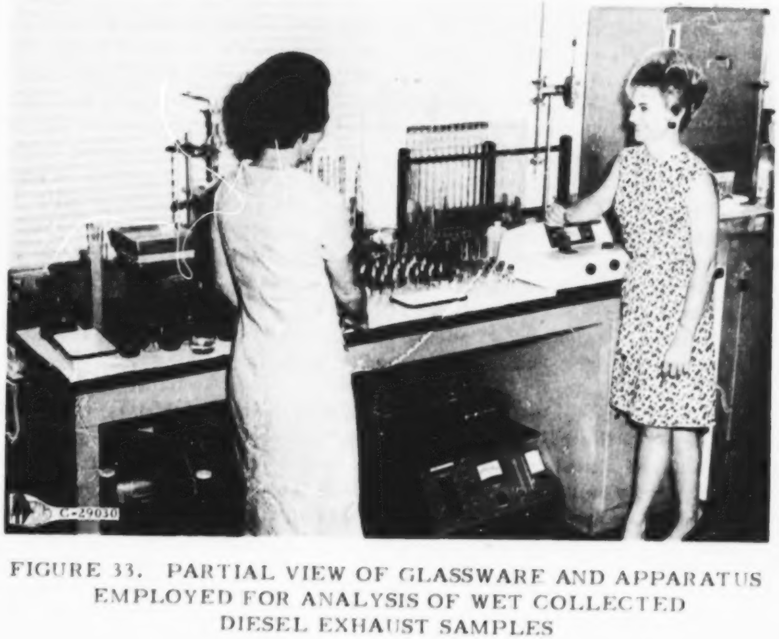


FIGURE 33. PARTIAL VIEW OF GLASSWARE AND APPARATUS EMPLOYED FOR ANALYSIS OF WET COLLECTED DIESEL EXHAUST SAMPLES

two-cycle engine indicated that even 100 liters of gas were not sufficient under a known heavy odor condition to produce high enough color readings for use of the Nestler color comparison tubes. Bus operation on the chassis dynamometer must be limited to about 3 to 5 min under the constant speed, heavy load conditions due to tire heating and hazards of tire failure. Practical sample rates with laboratory-size glassware and satisfactory absorption efficiency are generally limited to 1 and 2 liters/min for 10 and 20 ml of absorbing reagent, respectively. The use of large bags to obtain 75 to 150 liters for later bubbling through an aqueous solution of bicarbonate of soda appeared unwieldly and undesirable because of the possibility of odor degradation within the bag during the approximately 1 to 2 hr required to absorb. Accordingly, and with the knowledge of the Project Officer, experiments with the bicarbonate of soda method were discontinued.

B. Odor Correlation Chemistry

The other objective of this portion of the program was to study an instrument method that might relate to the odor panel ratings. A preliminary feasibility study was undertaken to determine the potentialities of using a gas chromatograph (GC) to separate the complex diesel exhaust into suitable groupings for detection by either flame ionization or electron capture techniques. The original approach was to take either raw or diluted diesel exhaust and insert this gas on a suitable column. The sample would then be grouped and eluted from the chromatograph through a stream splitter. One part of the split would pass to the detector for indication on a strip chart recorder. The other part would immediately pass from the chromatograph for analysis by a trained odor panelist. This approach had promise of being able to correlate peaks or groups of peaks with the PHS odor quality/intensity rating kit.

The initial objectives of this preliminary investigation were: (1) a study of the chemical nature of the odorant or odor precursor (hydrocarbon types, polar and nonpolar compounds, etc.), (2) selection of an appropriate GC sampling technique and sample location, (3) to obtain sufficient background to determine GC column needs and operational requirements. The gas liquid chromatograph (GLC) available for use in this study was a Varian Aerograph 600D equipped with stream splitter.

1. Initial Familiarization

To assist in the familiarization and preliminary experimental studies, a stable source of characteristic, two-cycle, diesel engine exhaust was necessary. A completely equipped stationary test bed engine-dynamometer facility was located adjacent to the analytical laboratory as close as possible to the common central laboratory exhaust stack used with buses and trucks. This exhaust stack provided the small amount of sample used for dilution and presentation to the odor panel. A single-cylinder, two-cycle GM 1-71 engine similar to the popular multicylinder two-cycle 71 series engine was made available. During familiarization studies conducted with this engine, it was found, using several trained odor panelists, that merely bubbling the exhaust through water effectively removed the odor. If the bubbling rate was increased sufficiently, the effectiveness of the scrubbing action decreased with less odor removed. The resulting odor quality and intensity was similar to changing the dilution ratio for the odor panel. The panelists also found that the head gas above the scrubbed exhaust in aqueous solution smelled essentially the same as diesel exhaust. This was confirmed by a number of laboratory personnel on several occasions. Apparently, the water scrubbing was effective in removing the characteristic diesel odor from the 1-71 engine exhaust.

Additional studies revealed that characteristic diesel odor may be changed in its odor quality and intensity by passing the exhaust gas through Tygon plastic tubing. These investigations were conducted using the usual stainless steel, Teflon, and Pyrex sampling systems but with a small dynapump, a diaphram type vacuum pump. The discharge side of the pump was fitted with a small Pyrex funnel for odor evaluation by the two odor panelists in turn. When an all Teflon and stainless steel glass system was employed, odor panelists rated the exhaust as "D"-7, noted the characteristic diesel odor (burnt-smoky, sweet, kerosene type odor) was preserved, and said the sample was realistic. When a 30-in. long piece of 1/4-in. ID Tygon tubing was substituted between the pump inlet and the source of exhaust, the resultant odor was quite different. In a sense, it was similar to some odors from automobile exhaust in that the odor was adjudged to be very sour and pungent. The overall diesel rating was reduced slightly to about "D"-6, but the important change was in the quality of the odor. The characteristic diesel exhaust odor had disappeared with essentially a new type of odor remaining. The burnt-smoky character was lost as was the sweetness and kerosene fuel smell. These experiments, conducted only with the 1-71 pilot engine, were repeated numerous times at various sampling locations, and this trend was confirmed. It is well known that Tygon tubing is a good absorber of various hydrocarbons and other exhaust constituents. Consideration was given to potential use of powdered or pulverized Tygon material in a chromatographic column for the selective removal of certain portions of the diesel exhaust.

The next step was to perform a brief study of the effect of selected fuels and fuel components on odor panel response using the 1-71 pilot engine. Before conducting this sequence of experiments, however, a number of operating conditions with this stationary mounted engine were explored to determine a single stable operating condition that would result in odor quality and intensity close to that generally obtained from buses powered by two-cycle engines.

It was determined that stable engine operation could be repeatably obtained at 1000 rpm, 10-hp output with the commercial number 1 kerosene type diesel fuel, EM-3-F, normally used in city buses. A dilution ratio of 100:1 was used, which resulted in "D," "B," "O," "A," and "P" ratings close to that obtained during Part I. Due to the low fuel consumption of 5.8 lb per hr at 10 hp, 1000 rpm, and the proximity of the fuel supply to the transfer pump and unit injector, it was found that at least two and sometimes three odor evaluations could be conducted with a quart of fuel. The 1-71 engine was useful, therefore, due to its low fuel requirements and the simplicity in changing fuels.

The results of the brief pilot study on the effect of fuel on odor are summarized on Tables 33 and 34 for the following fuels:

Fuel Code	Fuel Description
EM-3-F	Commercial number 1, kerosene type diesel fuel typically used in city bus operation.
EM-21-F	Up to 77-percent cut of number 1 diesel fuel (EM-3-F) obtained by vacuum distillation technique.
EM-22-F	Heavy 21.5-percent bottom cut residue of number 1 fuel (EM-3-F) by vacuum distillation technique.
EM-23-F	Saturates comprising 40-percent aviation alkylate, 40-percent isoparaffins and 20-percent cetane by volume.
EM-12-F	Commercial number 1 diesel fuel (EM-3-F) with experimental odor modifying additive.

The commercial number 1 kerosene type diesel fuel, coded EM-3-F, was the same material used during Part I. Included on Table 2 of Section II are the results of the fuel inspection of EM-3-F. To obtain EM-21-F and EM-22-F, a vacuum distillation of EM-3-F was made from 30°F and 1.1 mm Hg to 58°C and 0.1 mm Hg. Vacuum distillation was used to preserve the fuel constituents in essentially their normal conditions. The 77-percent cut would represent most of the material by conventional distillation up to around 420° to 430°F; however, the distillation curve under the vacuum technique was different from that with the atmospheric technique. The saturates, coded EM-23-F, may be described as a mixture of 40-percent aviation alkylate (a refinery cut consisting of 97-percent mixed light paraffins); 40 percent of 100-percent isoparaffins in the 420° to 430°F boiling range; and 20-percent cetane, which was added to bring the cetane number up to about 35 and prevent excessive engine knock. The runs with EM-12-F, the number 1 diesel fuel with experimental odor modifier, were conducted to determine if this particular engine condition would result in a different exhaust odor characteristic when operated with a treated fuel.

TABLE 33. RESULTS OF PILOT STUDY OF THE EFFECT OF FUEL PORTIONS ON EXHAUST ODOR

Engine: Detroit Diesel 1-71
Engine Speed: 1000 rpm

Date: June 12, 1967
Engine Load: 10 bhp

Fuel		Diesel Composite "D"	Average Small Panel Odor Quality/Intensity Rating				
Code	Description		First Most Obvious	Second Most Obvious	Third Most Obvious	Fourth Most Obvious	Comments
EM-3-F	No. 1 diesel	7.7	"B"(2.4)	"O"(2.3)	"A"(1.8)	"P"(0.3)	Kerosene, smoky, oily and sweet odors, similar to bus
EM-21-F	Up to 77 percent cut	7.6	"B"(2.6)	"O"(2.0)	"A"(1.8)	"P"(0)	Sweet and smoky
EM-22-F	21.5 percent residue	9.0	"B"(3.1)	"O"(3.0)	"A"(2.0)	"P"(0.7)	Strong and dusty
EM-23-F	Saturates	8.0	"B"(3.0)	"O"(2.6)	"A"(2.0)	"P"(0)	Smoky, dusty, similar to bus
EM-12-F	No. 1 diesel with odor modifier	7.0	"B"(2.0)	"O"(2.0)	"A"(2.0)	"P"(0)	Mint and sweet odor

TABLE 34. RESULTS OF PILOT STUDY OF THE EFFECT OF FUELS AND FUEL BLENDS ON EXHAUST ODOR

Engine: Detroit Diesel 1-71
Engine Speed: 1000 rpm

Date: June 15, 1967
Engine Load: 10 bhp

Fuel		Diesel Composite "D"	Average Small Panel Odor Quality/Intensity Rating				
Code	Description		First Most Obvious	Second Most Obvious	Third Most Obvious	Fourth Most Obvious	Comments
EM-3-F	No. 1 diesel	7.6	"B"(2.6)	"O"(2.7)	"A"(1.9)	"P"(0.4)	Smoky, oily, sweet, slightly sour, and similar to bus
EM-12-F	No. 1 diesel with odor modifier	7.2	"B"(2.2)	"O"(2.6)	"A"(1.8)	"P"(0.6)	Oily, sweet yet somewhat similar to bus
EM-24-F	50% cetane, 50% olefins	7.0	"B"(2.3)	"O"(2.0)	"A"(0.7)	"P"(0.3)	Oily with a burnt odor
EM-25-F	50% cetane, 50% aromatics	7.4	"B"(2.4)	"O"(2.8)	"A"(1.2)	"P"(0.4)	Oily, sweet, burnt, dusty odor
EM-26-F	Cetane	7.0	"B"(2.0)	"O"(2.2)	"A"(0)	"P"(0)	Burnt, oily odor
EM-27-F	n-Heptane (47 cetane number)	7.0	"O"(3.0)	"B"(2.0)	"A"(1.7)	"P"(1.7)	Oily, sweet odor
EM-28-F	n-Hetane plus 5% diesel lubricating oil 7.0	7.0	"B"(2.0)	"O"(2.0)	"A"(0.8)	"P"(0)	Burnt, oily, sweet odor

On Table 33, the small panel "D" rating is listed first, followed by the quality ratings on the basis of obviousness. Since the odor panel was trained to rate odor on the basis of obviousness, this capability was employed to express differences in fuels. In the last column of Table 33, pertinent comments regarding the odors are listed. For each of the quality ratings, the most obvious quality is listed, followed by its average intensity ratings in parentheses. Comparing the vacuum distillation condition against EM-3-F, almost identical odor ratings were given for the EM-3-F and EM-21-F, the 77-percent cut, and lower boiling end of EM-3-F. When the 1-71 engine was operated with EM-22-F (the residue of the vacuum distillation), a higher "D" rating of 9.0 versus 7.7 (for EM-3-F) was assessed. This was also reflected in the increase in the "B" quality from 2.4 for EM-3-F to 3.1 for EM-22-F. Additionally, the "O" rating went from 2.3 to 3.0 as did the "P" from 0.3 to 0.7. Compared to EM-21-F, EM-22-F showed similar, if not greater, increases in "D," "B," "O," and "P." The operation with a blended, saturates type fuel, EM-23-F, resulted in a "D" rating of 8.0, about the same as the 7.7 EM-3-F rating, and slightly higher "B" and "O" ratings relative to EM-3-F. In some ways, the EM-23-F was similar to the EM-22-F ratings especially by the comments that were given by the panelists. The number 1 diesel fuel with odor modifying additive, performed essentially as expected in that the "D" rating was not significantly affected, but the "B" rating was slightly decreased with a characteristic sweet and slightly minty odor resulting.

On June 15, 1967, additional experiments were made with a variety of fuels to determine further the influence fuel composition might have on exhaust odor. Using the one-cylinder pilot engine, the following fuels were evaluated:

Fuel Code	Fuel Description
EM-3-F	Commercial number 1, kerosene type diesel fuel typically used in city bus operation.
EM-12-F	Commercial number 1, diesel fuel (EM-3-F) with experimental odor modifying additive.
EM-24-F	A blend of 50-percent cetane and 50-percent olefins by volume.
EM-25-F	A mixture of 50-percent cetane and 50-percent aromatics by volume.
EM-26-F	100-percent cetane.
EM-27-F	100-percent n-Heptane with a cetane number of 47.
EM-28-F	A blend of EM-27-F (n-Heptane) plus 5 percent by volume of a typical diesel crankcase lubricating oil.

This series of experiments was intended to compare various pure fuels and blends of pure fuels against the number 1 fuel, EM-3-F. As in the previous sequence of experiments, each blend of pure fuel was evaluated back-to-back with EM-3-F. The overall average results are summarized on Table 34. Although the "D" ratings do not seem to change drastically with fuel type, it is interesting to compare, on the basis of obviousness, the "B" and "O" ratings and the comments that were made by the odor panel. When changing from cetane to n-Heptane, the panel consistently changed from "B" as being most obvious to "O" as being most obvious. The effect of adding diesel lubricating oil to the n-Heptane fuel resembled that obtained when operating with pure cetane or EM-3-F. The "D" rating was 7 for EM-26-F, EM-27-F, and EM-28-F, yet a significant reversal in quality obviousness occurred during these evaluations. To indicate how significant this reversal was, it may be likened to the difference between two- and four-cycle odor in that the "B" quality no longer was predominate and the oily and aromatic qualities were more noticeable.

2. Sampling and Sample Preparation

Consideration was next given to the second phase of the preliminary feasibility study, namely, sample location and preparation for introduction into the GLC. The initial studies included

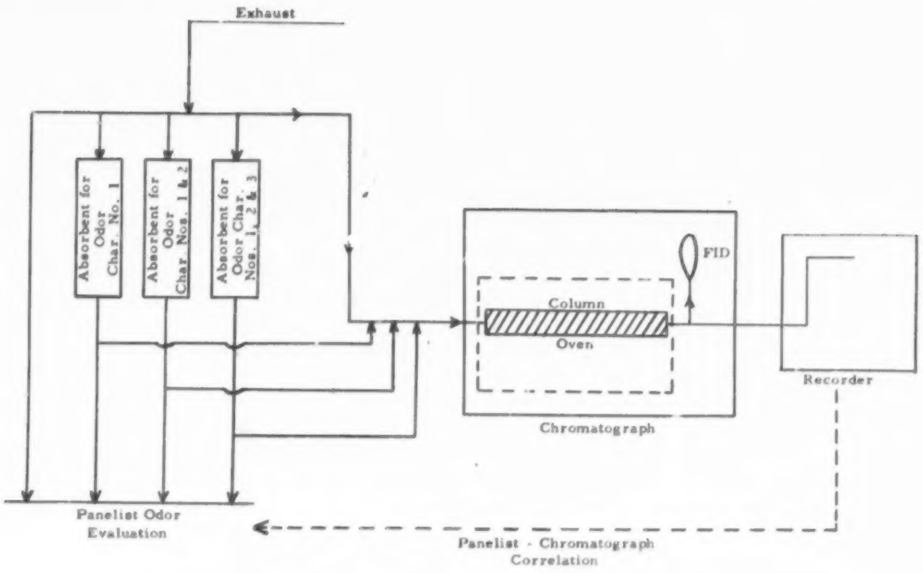

Exhaust
Absorbent for Odor Char. No. 1
Absorbent for Odor Char. Nos. 1 & 2
Absorbent for Odor Char. Nos. 1, 2 & 3
FID
Column
Oven
Chromatograph
Recorder
Panelist Odor Evaluation
Panelist - Chromatograph Correlation

FIGURE 34. SCHEMATIC FLOW DIAGRAM OF POSSIBLE ODOR PANEL--INSTRUMENT CORRELATION TECHNIQUE

a review of various chromatographic column materials, sampling, trapping, and interpretation of the resulting chromatograms. For simplicity, it was tentatively planned to employ a subtractive technique by which various portions of the diesel exhaust odor could be selectively absorbed or trapped prior to analysis by the chromatograph. Figure 34 is a schematic flow diagram of such a system. The raw exhaust would be passed through one or more different absorbents for the selected removal of various portions of the odor. The resulting odor from each of these various absorbents would then be evaluated by the small panel and compared to raw diesel exhaust. In addition, the effluent from the absorbers would be analyzed by a simple gas chromatograph system equipped initially with a flame ionization detector. This approach would then facilitate the correlation of the GC indication with the human evaluation.

One of the first precolumns (absorbents) tried was a short length of Tygon tubing packed with Tygon fragments located before the GC. This was effective in changing the GC indications, number of peaks, etc., in the chromatogram. Another technique used was a cold trap held at -70°C in which the raw diesel exhaust was first passed before being evaluated by the odor panel and the GC. It was found that the cold trap technique removed much of the burnt-smoky diesel characteristic odor such that a "D"-4 rating was given with the trap instead of the "D"-8 rating before the trap. The chromatograph, without preabsorbance, showed a characteristic single peak followed by a large hump-type peak. With the cold trap installed, the chromatograph indicated only the initial single peak representing light components, and the large hump-like peak characteristic of unburned fuel in the range of about C-6 to C-20 was not present. The GC was equipped with a 6-in. long, 1/8-in. diameter column packed with SE-30, and a constant temperature of 200°C was maintained.

During the familiarization studies, it was found that most diesel odorants from the single-cylinder engine were water-soluble materials. It was discovered that, when raw exhaust from the 1-71 engine was bubbled at a slow rate through water, practically all of the characteristic two-cycle odor was removed. Other type absorption traps such as solvents, ice baths and cold traps were considered and preliminary measurements as to their effectiveness obtained. In an effort to establish the relative effectiveness of various separation techniques and gain some insight as to the compounds trapped, the materials obtained by some of these techniques were subjected to mass spectrometric analyses. The procedure involved passing the raw diesel exhaust through suitable traps to obtain a sufficient quantity of separated materials to permit analysis and detection. This generally involved operating the 1-71 engine for a fairly long period of time. At the same time, a small panel comprised of two odor panelists evaluated the diesel exhaust odor before and after the trap. It was observed that the flow rate was a critical factor in terms of absorption efficiency. Thus, samples bubbled at flow rates greater than about 0.5 liter/min had insufficient absorption efficiency as illustrated by the relatively high "D"-6 rating noted. However, when the sampling rate was decreased to less than 0.5 liter/min, almost complete odorant absorption was observed for the apparatus employed.

Shown on Table 35 are mass spectrometric results which show a number of various compounds obtained by a cold trap held at -100°F and a water trap at 80°F. It is apparent that the cold trap and water trap both separated and collected essentially the same type of compounds even though the concentrations were greater with the water trap than with the cold trap. The reason for concentration differences may be the effectiveness of the water trap in collecting the water soluble materials relative to the initially dry cold trap. The water vapor in the exhaust collected in the cold trap as ice.

TABLE 35. DIESEL EXHAUST MASS SPECTROMETRIC ANALYSIS

Composition	Concentration, in ppm Cold Trap, -100°F	Water Trap, 80°F
Benzene	1	30
Toluene	1	39
Xylenes	1	131
C_9 Aromatics	0	13
Acetone and/or Propion Aldehyde and/or Methyl Vinyl Ether	6	15
Benzaldehyde and/or Styrene	2	16
Methyl Acrolein and/or Methyl Vinyl Ketone	8	19
Methyl Ethyl Ketone	3	3
Acetaldehyde	28	96
Methyl and/or Ethyl Alcohol	13	40
Acrolein	26	12
Propyl and Higher Alcohols	6	0
Water	Balance	Balance

Odor Panelist Evaluation	Before Either Trap	Balance After -100°F Trap*	Balance After 80°F Trap*
Diesel Composite	D^8	D^2	D^2
First Most Obvious	B^3	O^1	B^1
Second Most Obvious	O^3	A^1	A^1
Third Most Obvious	A^2	B^0	O^1
Fourth Most Obvious	P^0	P^0	P^0

---

*Flows were essentially the same under all conditions but not as low as required for complete removal of odor.

Shown at the bottom of Table 35 are the odor panelists' evaluation which shows the gross difference in the before and after trap ratings. The flows were essentially the same under all conditions, but the flow rates were not as low as required for removal of all odorants. Accordingly, the "after 80°F water trap" Q/I measurement indicated a small amount of "D," "B," "A," and "O" remaining in the sample. Reducing the flow rate or employing other techniques for more intimate scrubbing would permit essentially complete removal of the characteristic odor.

Figure 35 shows part of the laboratory arrangement employed for these preliminary studies. Undiluted diesel exhaust was obtained from the single-cylinder engine via heated 1/4-in. stainless steel probes. The engine was located on the back side of the wall in Figure 35. Exhaust samples were taken from the engine exhaust pipe located adjacent to the wall so that the length of heated sample tubing was approximately 8 inches. For purposes of this pilot study, only one engine condition, 1000 rpm at 10 hp, and one fuel, the commerical number 1 kerosene type fuel EM-3-F, were involved. The exhaust sample entered the laboratory through the 1/4-in. tubes (upper left-hand--Figure 35), filtered through a low residence, fiberglass media to remove smoke and carbon particulate, and passed either through the traps previously described, through the GC, or to one of two panelists. The odor panelist evaluates the exhaust presented in the small Pyrex glass funnel. The small dynapump shown, with Viton A diaphragm, was used when necessary to pump the sample through some of the trap systems and for presentation of the sample to the panelist.

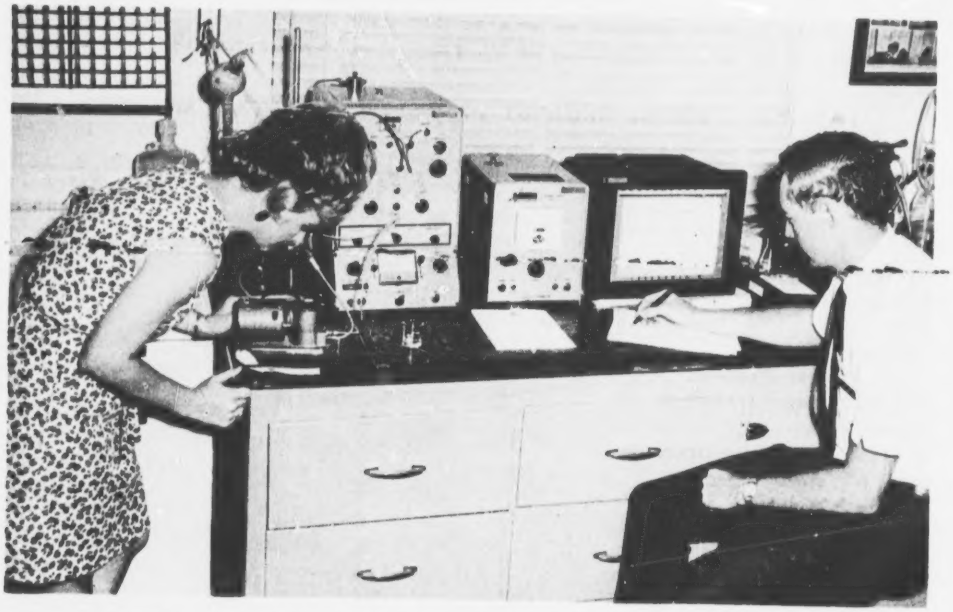


FIGURE 35. INSTRUMENT--SUBJECTIVE ANALYSIS ODOR CORRELATION--PILOT STUDY

During the pilot studies, an Aerograph 600D GLC was used to separate and detect constituents of interest. The output of the GC was displayed on the strip chart recorder equipped with disc integrator. During the pilot study with the single-cylinder engine, only the gross differences and overall trends were considered, and the subjective odor evaluations were conducted in the analytical laboratory instead of the environmental controlled odor room. A GC trace of raw exhaust was obtained and is shown in Figure 36. The exhaust components separation was made with a 15-ft × 1/4-in. column containing 15 percent SE-30 on Chromosorb W. After sample injection, the column oven was isothermally maintained for 7 min at 40°C. The column oven was then temperature programmed at a rate of about 15°C/min until 300°C, and then held at that temperature for the remainder of the analysis. Because of the minimum detectable limits of the flame ionization detector and the sample capacity of the column, the exhaust gas component separation was not satisfactory. Additional samples of gas were then passed through three CO_2-isopropyl alcohol cold baths in series held initially at -75°C and then at -35°C. The traces shown in Figures 37 and 38 indicate the "heavy ends"

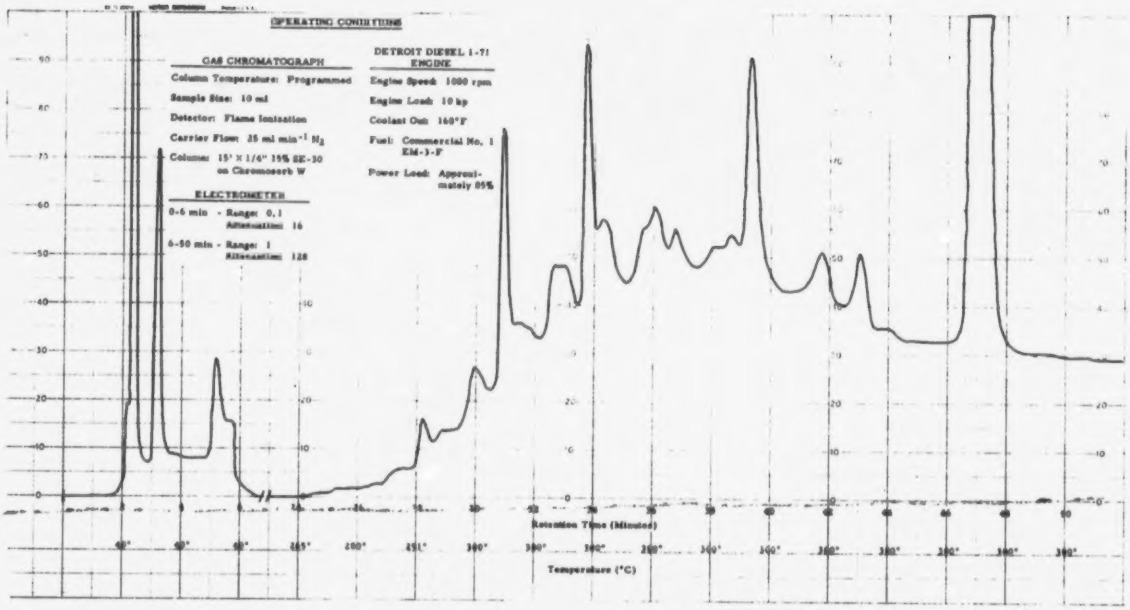


FIGURE 36. TYPICAL GAS CHROMATOGRAM OF DIESEL EXHAUST

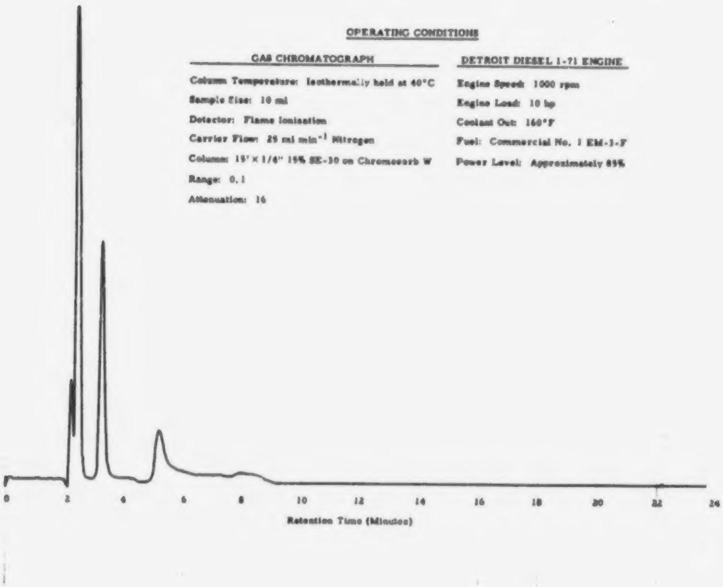


FIGURE 37. TYPICAL GAS CHROMATOGRAM OF DIESEL EXHAUST AFTER PASSING THROUGH THREE COLD TRAPS IN SERIES AT -75°C

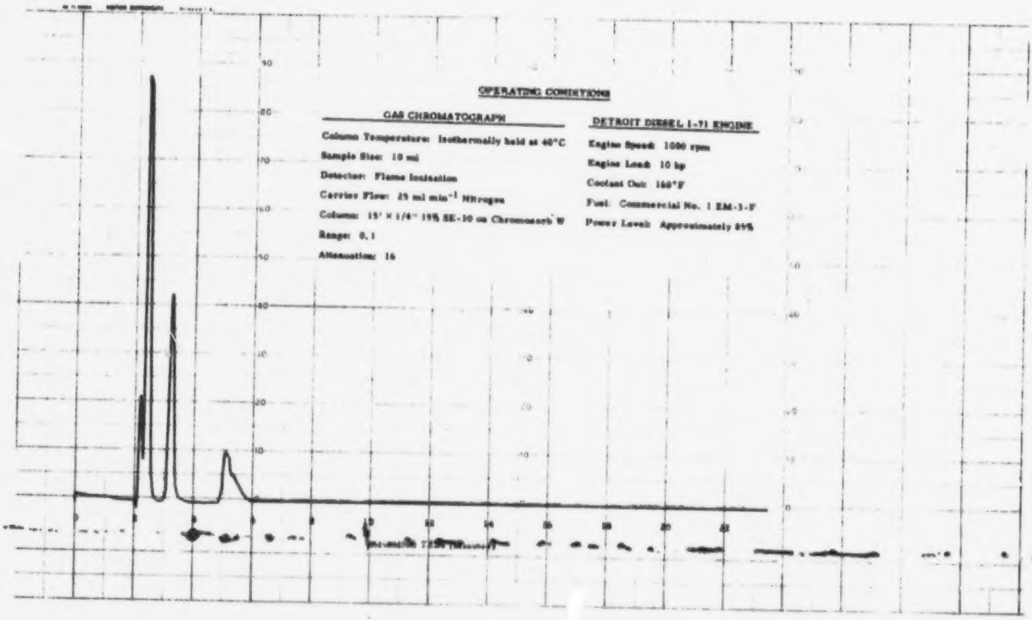


FIGURE 38. TYPICAL GAS CHROMATOGRAM OF DIESEL EXHAUST AFTER PASSING THROUGH THREE COLD TRAPS IN SERIES AT -35°C

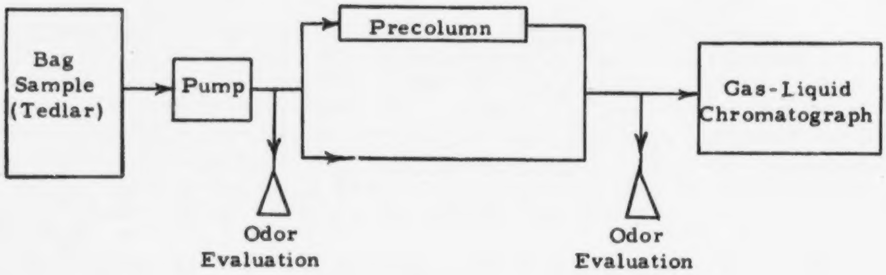
were removed by the cold traps. The odor intensity decreased from "D"-8 for the initial raw exhaust to a "D"-2 for the two samples which were routed through the cold traps.

The near 100-percent absorption of the odorous exhaust constituents in water indicated that the odorants were mostly polar components. The GC analysis also indicated that several components, probably light unburned hydrocarbons, were not absorbed by the water. The absorbed compounds were later analyzed by mass spectrometry, and some of these compounds listed on Table 35 have distinguishable odor characteristics. Experience to this point indicated that separation of a complex mixture of diesel exhaust via direct GC analysis was difficult. Since the mixture contained relatively large amounts of unburned fuel (nonpolar compounds) and partially oxygenated hydrocarbons (polar compounds such as aldehydes, ketones, ethers, etc.), it became evident that one column could not handle the complete analysis. If a column were packed with a nonpolar material, the polar materials would elute simultaneously with the nonpolar compounds, and the polar compounds would have a tendency to cause severe tailing. Conversely, the same problem would be encountered in trying to separate the mixture on a polar column. The two columns that were used in the gas chromatograph analysis of straight diesel exhaust were:

- Polar: 15-ft × 1/4-in. Al with 50/80 mesh Porapak Q
- Nonpolar: 15-ft × 1/4-in. Al with 15 percent SE-30 on 60/80 mesh Chromosorb W

Various operating conditions were used with each of these columns, and, in all cases, the straight diesel exhaust was too complex for direct analysis.

Previous experience showed that polar columns have much greater retention time for the unburned hydrocarbons than the nonpolar columns have for the polar compounds. In other words, the retention times of a C_9-C_{16} would be considerably longer on the polar column than would the retention times of the aldehydes, ketones, etc., found in exhaust on the nonpolar column. On the basis of this separation, efforts were directed toward finding a particular method which would remove the heavy unburned hydrocarbons from the fuel but allow the odor intensity to remain at the same relative level. The method used in this approach is described in the following schematic:



The sample, taken in a 2-cu ft Tedlar bag from the GM 1-71 engine, was transferred by means of a Model 3 dynapump with Viton A diaphragm through the "precolumn" and then into the GC. Odor evaluations, made before and after the "precolumns," are shown in Table 36. The "precolumns" were first evaluated in terms of lab air to determine whether or not the "precolumn" had any odor itself. Some of these materials were prepared by various chemical processes and could possibly have contained various residual solvents. These columns all had some residual solvent odor, as shown by the first column in Table 36. The Porapak Q columns appeared to have the least odor of any of the "precolumns" evaluated. Due to inherent dilution with room air, the samples were considered to be diluted to approximately 10 to 20:1 before being sniffed. The panelists took turns sniffing before and after the column and recorded their separate ratings. The individual "D" and the four quality ratings were averaged to obtain the scores shown on Table 36. The "D" intensity rating is shown first (by the superscript number ranging from 1 through 12, 12 strongest) followed by the four quality ratings made on the basis of obviousness. The superscripts for the four qualities can range from 0 through 4, 4 being the strongest and 0 meaning "not perceptible."

TABLE 36. SMALL PANEL EVALUATION OF PRECOLUMN EFFECTIVENESS ON ODOR REMOVAL

Precolumn	Lab Air Through Column*	Lab Air Through Column†	Diesel Exhaust Through Column	Lab Air Through Column After 5 Minutes of Diesel‡
6-in. Carbowax 1500	$D^6B^2O^2P^1A^1$	$D^5O^2P^1B^1A^1$	$D^6O^2P^2A^1B^1$	
24-in. Carbowax 1500	$D^6B^2O^2P^1A^1$	$D^4O^2P^1B^1A^1$	$D^6O^2P^2A^1B^1$	$D^5B^2O^2P^1A^1$
6-in. Glass beads	$D^5O^3B^1A^1P^1$	$D^5O^3B^1P^1A^1$	$D^8O^3B^2P^1A^1$	
24-in. Glass beads	$D^5O^3B^1A^1P^1$	$D^5O^3B^1P^1A^1$	$D^7O^3B^2P^1A^1$	$D^6O^3B^2P^1A^1$
6-in. Glass wool	$D^6O^3B^1P^1A^1$	$D^3O^1B^0A^0P^0$	$D^6O^2B^2P^1A^1$	
24-in. Glass wool	$D^6O^3B^1P^1A^1$	$D^3O^1B^0A^0P^0$	$D^6O^2B^2P^1A^1$	$D^6O^3B^1P^1A^1$
6-in. Chromosorb P	$D^5A^1P^1O^1B^0$	$D^4A^1P^1O^1B^1$	$D^5A^1P^1O^1B^1$	
24-in. Chromosorb P	$D^5A^1P^1O^1B^0$	$D^4A^1P^1O^1B^1$	$D^5A^1P^1O^1B^1$	$D^7O^2P^1A^1B^1$
6-in. Porapak Q	$D^3A^1P^1O^1B^0$	$D^2O^1A^1P^0B^0$	$D^2O^1A^1P^0B^0$	
24-in. Porapak Q	$D^3A^1P^1O^1B^0$	$D^2O^1A^1P^0B^0$	$D^2O^1A^1P^0B^0$	None

---

*Lab air pumped through the column. No between run cleaning performed.

†Lab air pumped through the column. After every sample, the pump was cleaned and made odor free to insure no odor contamination of past samples.

‡Lab air was evaluated after diesel exhaust was passed through the column for about 5 minutes.

Another series of odor ratings was conducted to insure that the dynapump had not contributed to the odor intensity observed. This was done by injecting small quantities of acetone into the pump and waiting until all residual diesel and acetone odor had disappeared. Before each "precolumn" odor evaluation, this procedure was performed. The results of these evaluations, listed in the second column of Table 36, were slightly less in most cases, usually in the order of one "D" rating unit, compared to the noncleaning procedure results. The diesel odor after passing through the "precolumns" was generally higher in intensity than that of the background odor of the "precolumns" (cleaned or noncleaned pump) and slightly less than the straight diesel intensity rating of "D"-8, "B"-2, "O"-2, "A"-1, and "P"-1.

A series of experiments was then performed to determine "precolumn" effectiveness. As shown by the results in Table 36, a great portion of the odor passed through several of the columns. The remaining question was whether or not the unburned hydrocarbons were passing through the column along with the odor. Samples of diesel exhaust were then passed through 6-in. and 24-in. × 3/16-in. columns packed with various materials. The exhaust was evaluated before and after the "precolumn" for total unburned hydrocarbons. Exhaust was taken from the Tedlar sampling bag by means of the dynapump, forced through the "precolumn" and then into a Beckman total hydrocarbon analyzer. Absolute results were not expected from this technique but only relative changes in total hydrocarbons. As shown in Table 37, the "precolumns" packed with glass beads and glass wool had very little effect on separating the hydrocarbons from the total exhaust. The "precolumns" packed with Porapak Q had too much efficiency; i.e., the column not only removed the hydrocarbons but the odor as well. Since odorous samples containing little or no unburned hydrocarbons (fuel) were desired, this column appeared to have no use. The two columns which appeared to have the best possibilities in terms of removing the hydrocarbons from the total exhaust without jeopardizing the odor were the 24-in. Carbowax and Chromosorb P columns. Analysis of total aldehydes before and after the columns indicated that both columns had the same aldehyde removal efficiency. The initial diesel exhaust had a total aldehyde concentration of 17.6 ppm "as-measured" and unadjusted for inherent exhaust dilution. Effluent from both columns gave a total aldehyde concentration of approximately 8.5 ppm. From the odor, hydrocarbon removal efficiency, and aldehyde analysis, it was determined that the 24-in. Carbowax 1500 and 24-in. Chromosorb P columns were optimum.

Diesel exhaust samples were then evaluated in the GC using the two above-mentioned "precolumns." Samples were evaluated in both "precolumns" with two differenct GC columns. The first GC column was a 15-ft × 1/4-in. Al with 15 percent SE-30 on 60/80 Chromosorb W. This column, used during previous analysis of diesel exhaust samples, gave good separation of the total diesel exhaust. The residual exhaust, after passing through the two "precolumns, gave no distinctive diesel peaks. This indicated that the "precolumns" were effective in removing the hydrocarbons from the total exhaust. No distinct sharp peaks were observed from the exhaust after it passed through the "precolumns" with the SE-30 GC column. This was expected when attempting to separate the polar from the nonpolar compounds. Several "humps" were observed, however, which were characteristic of polar compound separation on a nonpolar column. Consequently, these two "precolumns" were evaluated using a 15-ft × 1/4-in. Al 50/80 Porapak Q column in the GC. Although several small peaks were observed, it appears that the sensitivity limits of the GC had been reached.

Preliminary work indicated promise in two areas for potential trapping of the exhaust and possibly for concentration of the odorous constituents. At first, it was thought that cold traps would remove the hydrocarbons from raw exhaust and allow the odor to pass through. This was found not to be the case, as either the exhaust odor was trapped or the exhaust odor passed through the traps. Trap temperatures investigated included -76°, -35° and 0°C. At -76° and -35°C, all exhaust odor was trapped, and no odor or unburned hydrocarbons resulted. At 0°C, it was found that both unburned hydrocarbons and odor passed through the traps. For separating the hydrocarbons from the exhaust, this approach had very little promise. An offshoot of the low temperature cold trap approach was the elevated temperature separation. A series of six traps was prepared and placed in a mineral oil bath. Straight exhaust was passed through the traps at various temperatures and evaluated by an odor panelist in terms of odor intensity and quality. Temperatures investigated in this approach were 25°C, 50°C and 100°F. In all cases, the hydrocarbons and odor passed through the traps. Therefore, the cold and hot traps were abandoned as far as removing the hydrocarbons from the total exhaust. The other method of exhaust concentration was the water absorption technique which will be discussed in later paragraphs.

TABLE 37. "PRECOLUMN" HYDROCARBON SEPARATION EFFICIENCY

Precolumn	Hydrocarbon, ppm C*
6-in. Porapak Q	None
24-in. Porapak Q	None
6-in. Glass beads	115
24-in. Glass beads	200
6-in. Chromosorb P	105
24-in. Chromosorb P	15
6-in. Carbowax 1500	140
24-in. Carbowax 1500	40
6-in. Glass wool	150
24-in. Glass wool	145
Straight diesel	150

---

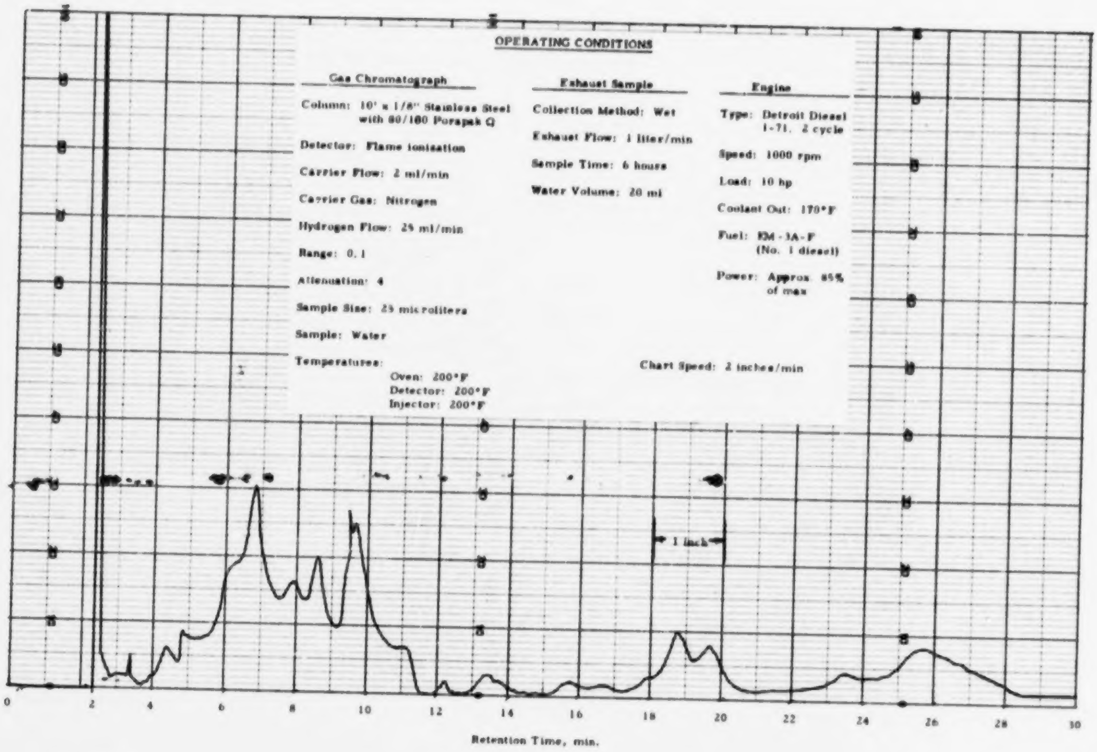
*Readings are intended to indicate relative effectiveness of precolumns on hydrocarbon removal and are not absolute.

3. GC Column and Operational Requirements

Due to lack of promise by GLC analysis of the effluent of the 24-in. Carbowax and Chromosorb P "precolumns," liquid injection of the water trapped diesel exhaust was reconsidered. The mass spectral data indicated that the polar compounds present in the exhaust solution were mostly aldehydes, ketones and alcohols. On this basis, several columns, described on Table 38, were prepared. Carbowax 20M has been reported to be an effective liquid phase for the separation of aldehydes, while FFAP is effective in the complete removal of aldehydes. This would indicate that certain liquid phases might have specific application in the removal of certain chemical species from the gas chromatograph sample.

TABLE 38. GAS CHROMATOGRAPH COLUMN DIMENSIONS AND PACKING PROPOSED FOR USE IN REEVALUATION OF WATER ABSORBED DIESEL EXHAUST

Column						
Length, ft	Diameter, in.	Material	Conc., %	Liquid Phase	Mesh	Support
3	1/8	SS	10	Carbowax 20M	60/80	DMCS-AW Chrom P
6	1/8	SS	10	Carbowax 20M	60/80	DMCS-AW Chrom P
3	1/8	SS	10	FFAP	60/80	DMCS-AW Chrom P
6	1/8	SS	10	FFAP	60/80	DMCS-AW Chrom P
3	1/8	SS	-	Porapak Q	80/100	-
6	1/8	SS	-	Porapak Q	80/100	-



OPERATING CONDITIONS

Gas Chromatograph

Column: 10' x 1/8" Stainless Steel with 80/100 Porapak Q
Detector: Flame ionization
Carrier Flow: 2 ml/min
Carrier Gas: Nitrogen
Hydrogen Flow: 25 ml/min
Range: 0.1
Attenuation: 4
Sample Size: 25 microliters
Sample: Water
Temperatures:
Oven: 200°F
Detector: 200°F
Injector: 200°F

Exhaust Sample

Collection Method: Wet
Exhaust Flow: 1 liter/min
Sample Time: 6 hours
Water Volume: 20 ml

Engine

Type: Detroit Diesel 1-71, 2 cycle
Speed: 1000 rpm
Load: 10 hp
Coolant Out: 170°F
Fuel: EM-3A-F (No. 1 diesel)
Power: Approx. 85% of max

Chart Speed: 2 inches/min

FIGURE 39. TYPICAL GAS CHROMATOGRAM OF WATER COLLECTED EXHAUST ODORANTS FROM LABORATORY TWO-CYCLE ENGINE

Although experimentation with the columns listed on Table 38 was limited and not as extensive as desired, it was found that injection of water collected samples of diesel exhaust odorants onto a Porapak Q column resulted in a series of definable peaks. A typical chromatogram thus obtained is shown in Figure 39. The initial high peak was identified as the response of the flame ionization detector to the water vapor from the injected sample established by similar experiments in which the single characteristic peak was obtained when pure water alone was injected. The remainder of the chromatogram represents the various water absorbed exhaust odorants from the single-cylinder, two-cycle laboratory engine. Although it is not known for certain, these materials are suspected to be basically polar in nature, typified by partially oxygenated materials such as aldehydes, ketones, esters, and possibly ethers. For the Porapak Q material in the 1/8-in. × 10-ft column, these general types of compounds would be expected to be separated. The retention times for the various compounds appear to be similar to those predicted from mass spectrometric data for the Porapak Q column employed. Although the chromatogram shown in Figure 39 appears promising, a substantial amount of experimentation and development remains in order to determine instrument procedure, establish repeatability, and reliability.

4. Summary

The use of water absorbed analyses appears promising since water seems to be an effective method for the removal of most, if not all, of the perceptible odorants in raw diesel exhaust. By efficiently bubbling at a low enough rate, essentially all of the diesel exhaust odor was removed from samples obtained continuously from 1-71 engine operated at 1000 rpm near maximum power. It is conceivable, using Tedlar plastic bags, that samples of raw diesel exhaust could be obtained during a constant speed operating condition (for example, an idle) of approximately 3 min in duration. Immediately after sample collection of the exhaust, the majority of the contents would be bubbled at an optimum rate for effective removal of odor through a cylindrical fritted bubbler containing 10 ml of pure water. By knowing the sample flow rate (approximately 1 liter/min) and the sample duration along with the absorbing water quantity, the GC analyses may be related to concentrations in the exhaust gas.

In addition to its inherent simplicity, another important advantage of the water absorption technique is that any condensed unburned fuel, heavy hydrocarbons, etc., are basically insoluble in the water phase and are effectively separated from those materials that are water soluble, such as the polar materials previously pointed out. As a result, the water absorption technique holds promise in removing the bulk of the unwanted unburned fuel. The procedure appears to have a few disadvantages which can be minimized if sampling is limited to the idle condition. The idle condition has generally been rated as one of the conditions which produces substantial odor levels. From investigations conducted during the evaluation of catalytic mufflers, it was found that the "as-measured" concentrations of the various polar materials such as aldehydes, etc., were fairly high during the hot-idle condition, even though there was a substantial amount of excess air present in the exhaust. At idle, little or no carbonaceous particles, soot, etc., are produced, and the excess air in the exhaust tends to minimize condensation of the water vapor (very little fuel is consumed during idle). Consequently, the idle tends to minimize problems of condensation, aerosols and particulate transfer of odorants. By having little or no particulate matter present, the need for filtration by means of fiber glass or other filter media may be practically overlooked. What few particles of soot, etc., that are present (and could act as carriers for various odorants) may fall out of suspension and not seriously endanger the efficiency of the fritted cylindrical absorber. By having little additional water vapor due to combustion of the fuel at idle, the potential for substantial amounts of water condensation within the sample bag is minimized. The final remaining disadvantage foreseen with the bag sampling technique is the possibility of a change in diesel exhaust composition with time. The large excesses of air, however, handled by the engine during idle, appear to serve as an effective diluent and quench for these interactions. No perceptible odor changes were found with the hot idle exhaust, from a two-cycle E series and a four-cycle V8 powered bus, stored in large Tedlar bags and evaluated hourly during a period of several days by a small panel in the odor room. In conclusion, it seems that the water-collected odor samples, analyzed by GLC and by mass spectrometry, appear to be a practical and potentially usable technique for correlation with the odor panel.

IX. VARIOUS DIESEL EMISSIONS MEASUREMENTS

In the original description of this Part II program, provision was made to conduct a limited evaluation of the effect of fumigation on smoke and odor emissions from a two-cycle powered municipal bus. Fumigation means to add up to approximately 10 percent of the normally injected diesel fuel directly to the intake manifold of a diesel engine. Under the Part I program, fumigation was investigated in a Cummins NH-220, four-cycle, naturally aspirated diesel engine in the dynamometer laboratory. The results indicated the effect of fumigation on exhaust smoke was dependent on the residence time in the combustion chamber of the fumigant. In other words, if the engine speed increased from 900 rpm up to the normal operating range of 1700 to 2100 rpm, the smoke reduction effectiveness decreased substantially. As recommended in the Part I Final Report, the minimum smoke reduction available with fumigation under normal operating speeds of 1700 to 2100 rpm did not justify additional research with this method as a smoke reducing technique. Accordingly, it was recommended that the limited level of effort under this phase be applied to the other phases of this program and that fumigation as a means for reducing smoke and odor be eliminated from consideration.

During the last several months of Part II, it became evident that a number of diesel emissions measurements involving a limited level of effort were of importance to the Public Health Service. It was suggested that the results of these studies be reported in a "various diesel emissions" category. The four studies which logically belonged in this "various" category included:

(1) A limited study of smokemeter readings as a function of exhaust pipe diameter,

(2) Preliminary measurements using tentative PHS smoke procedures,

(3) Evaluation of the Gordine Systems electrostatic precipitator for removal of smoke particulate, and

(4) Acquisition of base line exhaust emissions from a Flxible coach powered by a four-cycle diesel engine.

A. Effect of Exhaust Pipe Diameter on PHS Smokemeter Readings

This limited investigation, requested on October 20, 1967, was conducted using the stationary, test bed mounted, Cummins NH-220, naturally aspirated, six-cylinder, four-cycle diesel engine operated on a known number 2 type diesel fuel (SwRI Code EM-29-F, see Section II for fuel description). The results of these experiments were submitted as a Special Status Report dated November 1, 1967, entitled "Investigation of the Effect of Exhaust Pipe Diameter and Exhaust Velocity on Smoke Readings Using a Full-Flow, Light-Extinction PHS Smokemeter" (Ref. 17). Because of the wide interest in the results of the study and because there were a few minor corrections, changes in terminology, etc., this special report has been included, in revised form, in this report. The term "opacity" has been used in place of the term "absorbance," used in the special report, to indicate smoke intensity. The two most widely used exhaust pipes or stacks with commercial diesel powered vehicles are generally 3- or 4-in. diameter. The 3-in. diameter pipe is commonly used with municipal buses powered by Detroit Diesel 6V-71 engines. Exhaust pipes in use with diesel powered intercity truck-tractors may vary between 3- and 5-in. diameter and generally are 4 in. in size. Tractors powered with increasingly larger displacement engines are being equipped with stacks larger than 4 in., and, therefore, it was considered that a larger size stack should be investigated. Therefore, smoke readings were planned under comparable engine operating conditions with 3-, 4-, and 5-in. stack diameters. To obtain the requested 60-percent opacity reading, it was necessary to restrict the engine airflow from that normally handled by the Cummins NH-220 engine. Previous operation of this engine has shown smoke to increase with increasing engine speed and observed brake horsepower output. Therefore, a number of realistic engine operating speeds--1700, 1900 and 2100 rpm--were considered with the engine in the "as-is" condition with the fuel pump adjusted for NH-220 truck specifications. Following this set of measurements, an intake orifice, cut to allow up to about 40-percent smoke opacity, was immediately placed over the intake manifold flange, the same three speeds operated, and smoke measured. Following this, a second intake orifice, precut to result in about 60-percent smoke opacity, was immediately installed, the same three engine speeds operated in succession, and the resultant smoke monitored. The procedure involved doing this in triplicate with one size exhaust pipe and then installing a different size exhaust pipe, remounting the smokemeter to contain the full plume of exhaust, and repeating the procedure. This was continued until measurements were obtained with all three pipe sizes. Because of the urgency of this request, it was felt that engine airflow would not be measured and that a typical airflow versus engine speed curve, obtained from the manufacturer, would be utilized. This limitation in measured data did not influence the trends and results obtained due to the comparable conditions involved under each set of tests with each size pipe.

The engine exhaust configuration was essentially identical for each stack diameter in that the same muffler, same engine condition, same exhaust manifold pipe, etc., were used. Identical lengths of 3-, 4-, and 5-in. diameter pipes were connected to the outlet of the muffler by means of flexible pipe. The flexible pipe was of compatible size to the exhaust pipe investigated. In each case, the exhaust was carried through a straight length of smooth, inside wall pipe prior to its exit into the atmosphere and measured by the smokemeter. The straightening section of pipe was 4 ft for the 4-in. diameter pipe, 3 ft for the 3-in. diameter pipe, and 8 ft for the 5-in. diameter pipe. Seamless, mild steel, thin-walled exhaust pipe was used for the 3- and 4-in. pipes, and thin stainless steel duct was used for the 5-in. pipe.

Initially, the engine was operated to determine the applicability of the procedure and to become familiar with the level of smoke that could be expected. The results of this initial set of experiments with the normal 4-in. diameter pipe are listed in Table 1 of Appendix F. The 1700-, 1900- and 2100-rpm conditions were obtained first with the engine in the "as-is" condition and resulted in 12-, 15- and 17-percent opacity respectively. These same three speeds were again operated after the intake orifice for about 40-percent smoke was installed and resulted in an average of 26-, 32- and 41-percent opacity. These same three speeds resulted in 41-, 50- and 63-percent smoke with the smaller intake orifice installed. The centerline of the smokemeter light beam was located 5-1/2 in. above the tip of the 4-in. diameter stack. This resulted in the smokemeter containing the full plume of the exhaust.

Table 39 contains smoke readings obtained with various pipe sizes and summarizes the measurements listed in Tables 2 through 4, Appendix F. The results are arranged to show the difference in percent opacity for the 3-, 4-, and 5-in. diameter exhaust pipes at the three engine speeds investigated. Also indicated is the average observed engine power output and the exhaust backpressure in inches of mercury. In the "as-is" calibrated NH-220 truck condition, little or no difference was found between the 3- and 4-in. stack readings. This lack of significant difference was also noted when the intake orifices for about 40- and 60-percent smoke were installed. One exception, at 1700 rpm, was found between the 3- and 4-in. diameter pipes with the intake orifice for about 60-percent smoke installed. The average reading was 35 percent for the 3-in. diameter stack and 41 percent for the 4-in. diameter stack under comparable conditions. Although the difference of six points opacity at this single condition has not been resolved, it does not appear to alter the conclusion that for the experiments conducted there was little difference between the smoke reading obtained with the 3- versus the 4-in. diameter pipe. Contrary to the good agreement obtained between the 3- and 4-in. diameter pipes, it was found that when smoke readings were obtained with the 5-in. diameter pipe, the measured smoke was higher in all cases. Although the difference at the light end of the smoke scale was not but 2 to 3 points opacity, this difference increased as the smoke level increased for the engine "as-is." With the 40-percent smoke orifice installed, the readings with the 5-in. pipe were 7- to 9-percent opacity higher than with the 3- or 4-in. pipes. This difference became even greater when the 60-percent smoke orifice was installed and ranged from 10 to 12 percent higher than with the 3- or 4-in. pipe.

The data on Table 39 were summarized from measurements obtained with the 3-, 4-, and 5-in. OD exhaust pipes in rapid succession contained on Tables 2, 3, and 4 of Appendix F. The readings were obtained with the engine in the "as-is" condition, followed by similar engine speed conditions with the 40- and then the 60-percent smoke orifice installed. When the 3-in. diameter exhaust pipe was utilized, the smokemeter had to be located so that the centerline of the light beam

TABLE 39. SUMMARY OF PHS SMOKEMETER READINGS VS PIPE SIZE AND EXHAUST FLOW

(From Tables 2 - 4 of Appendix F)

Stack Diameter, in. OD	Stack Area, sq in.	Engine Speed, rpm	Exhaust Velocity, FPM	Engine Airflow, CFM*	Engine Output, obs BHP	Exhaust Backpressure, in. Hg	PHS Average Reading, % Opacity
Engine "as-is"							
3	6.48	1700	7340	330	187	1.8	13
		1900	8220	370	201	2.2	15
		2100	9020	406	221	2.7	18
4	11.75	1700	4050	330	184	0.8	13
		1900	4540	370	200	0.9	15
		2100	4980	406	217	1.1	17
5	18.95	1700	2520	330	178	0.6	15
		1900	2820	370	194	0.6	19
		2100	3100	406	214	0.7	21
Intake orifice for about 40% smoke installed.							
3	6.48	1700		(1)	174	1.75	23
		1900		(2)	187	2.05	30
		2100	Not	(3)	198	2.35	40
4	11.75	1700		(1)	171	0.85	24
		1900	Avail-	(2)	184	0.85	31
		2100		(3)	196	0.85	41
5	18.95	1700	able	(1)	165	0.6	30
		1900		(2)	177	0.6	42
		2100		(3)	193	0.62	49
Intake orifice for about 60% smoke installed.							
3	6.48	1700		(4)	166	1.7	35
		1900		(5)	176	1.8	50
		2100	Not	(6)	184	2.1	60
4	11.75	1700		(4)	158	0.85	41
		1900	Avail-	(5)	170	0.75	52
		2100		(6)	182	0.8	63
5	18.95	1700	able	(4)	158	0.6	47
		1900		(5)	170	0.53	62
		2100		(6)	177	0.55	70

---

*Numbers in parentheses mean that exhaust flows, CFM, were identical and may be directly compared.

was 9-1/4 in. above the tip of the stack to contain the full plume of exhaust. The exhaust velocity for the engine in the "as-is" condition was 7340 fpm at 1700 rpm, 8220 fpm at 1900 rpm and 9020 fpm at 2100 rpm for the 3-in. diameter stack. For the 4-in. pipe, Table 3, the exhaust velocities were 4050 fpm at 1700 rpm, 4540 fpm at 1900 rpm, and 4980 fpm at 2100 rpm. Backpressures, as measured at the inlet to the exhaust muffler (outlet of the exhaust manifold), were slightly less with the 4-in. diameter pipe than the 3-in. diameter pipe. With the 5-in. diameter exhaust stack, the backpressures, as shown in Table 4, were slightly lower than with the 4-in. pipe. These pressures may have been even less except for the fixed backpressure in the exhaust muffler. For the engine in the "as-is" condition, the velocities ranged from 2520 fpm at 1700 rpm to 3100 fpm at 2100 rpm. To contain the full plume of exhaust, the light beam was 4 in. from the exhaust pipe.

One reason that may be offered for the increase in smoke with the 5-in. diameter pipes would be the possible longer residence time of the exhaust in the larger diameter pipe and the increased possibility of quench or heat transfer which would affect the appearance of the exhaust. When an engine is operating under maximum power, the exhaust within 1 or 2 in. of the tip of the pipe remains clear for certain stack configurations. This has been attributed by some investigators to the incandescent nature of the carbon particulate as it exits the exhaust pipe. On exit from the pipe, however, a substantial amount of induced dilution with the atmosphere is initiated, and the invisible material assumes the characteristic visible black plume. The current procedure is to locate the aluminum ring, on which the collimating light source and photocell of the PHS smokemeter are mounted, so the full plume of the exhaust is contained within and fills the ring. As exhaust velocity is decreased due to an increase in pipe diameter, etc., the smokemeter ring and light beam must be moved closer to the tip of the stack. If some of the particulate matter has not completely turned black as it cuts the light beam of the smokemeter, the greater residence time at lower velocities may permit more complete quench. Coupled with the induced dilution on exit from the pipe, the exhaust particulate may have more completely converted to a black appearance.

B. Preliminary Studies with the Tentative PHS Smoke Test Procedure

This study was concerned with acquisition of smoke data using a PHS smoke test procedure per requests of October 12 and October 20, 1967. This 2-wk experimental project resulted in a special status report entitled "Preliminary Smoke Data with Turbocharged and Naturally Aspirated Diesel Engines" dated November 1, 1967, Reference 18. This report contained strip chart recordings of smoke intensity and engine rpm/vehicle mph for a variety of different types and makes of automotive diesel engines. Since duplicate charts are not available, only the tabular information (contained in Appendix F) and a revised version of the special report are included.

The initial test procedure for use in this investigation involved two modes, a quasi-constant speed and an acceleration described as follows:

(1) "With engine at max governed speed, the speed shall be decreased maintaining full load to a speed below peak torque speed that is equal to 90% of the brake horsepower at peak torque.

(2) "A full-rack acceleration from idle speed to a dynamometer load speed condition which is 85% of full load on the brake horsepower curve for the specific engine."

A set of exploratory runs, made with the stationary Cummins NH-220 engine loaded by means of a 300-hp Clayton water brake stationary dynamometer, illustrated that additional clarification would be necessary to the procedure to permit repeatable operation. Specifically, deceleration and acceleration rates seemed important, not only during the (1) part in which the engine was operated at full rack, maximum power from governed speed down to a speed equivalent to 90 percent of the brake horsepower at max torque, but particularly during the acceleration in (2) from idle to rated speed and load. Preliminary results using a modified procedure were reported which indicated that during the (1) run, the observed smoke output decreased as the engine speed decreased from the 2200 rpm down to 1300 rpm. Although the smoke measurements were obtained at steadily decreasing 100-rpm increments, the procedure was essentially identical to that described in (1). The acceleration condition was found to be unsatisfactory for purposes of the diesel smoke test. A number of minor points were raised regarding the (1) and (2) procedures originally described, such as the rate of acceleration already discussed and the definition of max torque. Certain engines have practically a flat torque curve, and, if manufacturers' characteristic curves for their particular engines are used, it may be difficult to establish the peak torque condition. Other engines may have a torque curve which continues to decrease or increase throughout the usable engine speed range and lack a definable published peak.

Tables 5 through 12 in Appendix F describe each diesel engine and tractor driveline arrangement studied and contain the lugging constant speed procedure (1) results such as vehicle speed, horsepower output and smoke opacity readings. The smoke readings in each case were read from a continuous strip chart trace of smoke opacity. Included are the calculations used to determine the lower speed to be investigated during each constant speed condition and the idle and governed speed of each engine. At the bottom of each table is a note regarding the acceleration made from idle to maximum rated engine speed.

On October 20, 1967, a number of procedures were investigated with a new International Harvester Model COF-4000D tandem axle tractor equipped with a five-speed transmission and three-speed Eaton rear axle. This tractor was powered by the new International DVT 573(260) engine which produces 260 hp at 2600 rpm. From the engine performance curves, maximum torque occurred at approximately 1900 rpm, at which point the gross power output was shown as 210 hp. Following the (1) procedure, 90 percent of 210 hp equals 189 hp, which corresponded to 1730 rpm. Therefore, the minimum speed was established as 1730 rpm. Some preliminary information with this tractor was obtained throughout the speed range of 2700 to 1200 rpm and is shown in Table 5 of Appendix F. Smoke from this new tractor increased from a reading of 12-percent opacity at 2700 rpm to 83-percent opacity at 1200. All of these tests were made with commercial number 2 diesel fuel. A continuous trace recording of smoke intensity was obtained with this tractor and forwarded to the Project Officer. The intent of these runs was to establish the smoke output under an acceleration condition from idle to rated speed and load conducted smoothly over a period of time in excess of 15 sec, as well as under condition (1). Although these runs were not conducted exactly according to the procedures as understood, the results indicated nonetheless that there was an appreciable smoke emission during the time required for the engine turbocharger to "catch up" with the operation of the engine, resulting in an acceleration condition which produced black smoke over a substantial duration.

It was found, on the particular tractor investigated, that without use of the SwRI inertia simulation system, an acceleration could be obtained by conducting the (1) portion of the procedure, and then returning to rated speed of 2000-rpm full power. Then, with the load retained in the water brake dynamometer, the clutch was disengaged and the engine allowed to idle for 3 min. Following this extended idle, with the engine and vehicle transmission in 13th gear, a fairly smooth acceleration was obtained back to 2000 rpm. This acceleration showed that heavy smoke was emitted at the beginning and during the acceleration from idle. A note may be made as to the realism of the acceleration from idle to maximum rated speed. In the operation of vehicles, upshifts normally occur over a specified range of engine speed. Generally, only during the very brief acceleration in the initial gear selected to move the vehicle from rest (1st gear) does the engine operate from idle speed of around 500 rpm up to its rated speed. The remainder of the time, the shifting speeds are generally near and greater than the max torque rpm condition. This will vary with driver, vehicle, driveline and engine type. To conduct the acceleration under more realistic shifting conditions may require the use of external devices with either engine or chassis dynamometer, such as inertia wheels, to simulate real vehicle operation. An alternate technique may be to operate at a light cruise power condition in a relatively high gear range of the transmission and at the lower end of the operable engine rpm. Then perform a full-rack acceleration against either inertia loads or dynamometer "Q" curve loading to reach the desired maximum condition. With the engine at the lower end of its shifting speed position, this may result in a typically encountered turbocharger lag. This alternate acceleration method may be found to be more desirable but more difficult to conduct in terms of dynamometer and equipment requirements.

On October 23, 1967, a tentative smoke measurement procedure was received as follows:

(1) "From rated power, the dynamometer control shall be adjusted to permit the engine to attain maximum speed; if higher than at rated output, this progressive adjustment shall be made to slow the engine at full rack below the speed of maximum torque to the point when observed brake horsepower is 90% of the observed brake horsepower at maximum torque. This procedure shall be accomplished smoothly during a period of no less than 30 seconds. The air supplied to the induction system inlet shall be at a temperature no less than 60°F and at a pressure no greater than sea level barometer.

(2) "Following sequence (1) above, the dynamometer and engine governor controls shall be adjusted to provide minimum idle speed; engine power output shall be no more than that required to overcome dynamometer rotor shaft bearing friction. If the engine is tested in a vehicle on a chassis dynamometer, the transmission shall be shifted into neutral and the clutch, if so equipped, shall be engaged. The engine shall be operated at this minimum idle speed no load condition for a period no less than 3 minutes, then a full-rack acceleration shall be made at no less than 85% rated brake horsepower at rated speed. Such acceleration shall be accomplished smoothly during a period of no less than 15 seconds. The acceleration can be accomplished with a manually-controlled electric dynamometer by progressively increasing the excitation current to a predetermined value; however, a hydraulic dynamometer may require special procedures and attachments such as mechanical inertia and/or a declutching device."

The first truck-tractor investigated was a tandem axle White Freightliner powered by a Caterpillar, turbocharged, aftercooled, Model 1676 diesel truck engine (rated horsepower of 340 at 2200 rpm). The remainder of the driveline consisted of a Road Ranger transmission

Model RTO-915 with single-speed tandem drive rear axles and 10.00 × 20 tires. This particular tractor was 1 year old, with the original engine intact. The intake air pipe and the exhaust stack were both 5-in. diameter. Other engine information is shown in Table 6 of Appendix F. From manufacturer's performance curves, it was determined that peak torque occurred at 1675 rpm which corresponded to approximately 300 hp; 90 percent of 300 hp is 270 hp, which corresponds to 1540 rpm as the lower speed of the (1) procedure. Shown on Table 6 of Appendix F are the engine speed-mph and horsepower output at the rear wheels. This tractor had approximately 100 hp more output than that achieved with the NH-220, naturally aspirated units tested in the past. As listed in Table 2, the smoke reading from the continuous chart did not reach above 20-percent opacity until the engine speed reduced to about 1600 rpm. Further decrease in speed resulted in a significant increase in smoke level. Above 1700 rpm, the smoke output from this tractor was judged light. During the acceleration to 2200-rpm procedure after a 3-min idle, there was a surge of smoke emitted at the initiation of the acceleration to 100-percent opacity followed by an immediate drop to around 60-percent opacity, which continued 3 to 4 sec. This was followed by a drop-off in smoke emissions as the engine accelerated to 2200 rpm. The acceleration required 20 sec by stopwatch to conduct. Operation of this type of vehicle above 1700 rpm and at quasi-constant conditions did not result in appreciable levels of smoke. As the engine speed was reduced below max torque speed, smoke levels increased substantially, about 15-percent opacity per 100-rpm engine speed.

To establish the loading to be used during the acceleration in (2), it was necessary to initially determine the part load power at 1540 rpm that would result in maximum power at 2200 rpm. Adjusting the water brake dynamometer to give full power absorption at 2200 rpm, the engine speed was lessened to a part-rack condition at 1540 rpm and the power output observed. In the case of this particular tractor, the power output at 1540 rpm was 108 hp. Therefore, after the smoke test procedure described in (1) was completed, the vehicle and engine speed was held at 1550 rpm and the load reduced from full power to the part throttle condition of 108 hp desired. As soon as this part-loaded condition was established, the engine was brought to an idle condition and the 3-min idle begun. With 108 hp preset in the dynamometer at 1540 rpm, the full-rack acceleration in 8th gear was conducted. The clarity and fidelity of the smoke recording with the 0- to 100-mv, single-pen recorder was less than desirable. It was to not only measure the smoke output continuously and with better resolution and tracking but also to record, simultaneously, either engine speed or vehicle speed depending on whether the test was being made on a chassis dynamometer or with a stationary engine stand. An available Texas Instruments, two-pen overlapping type strip chart 0- to 10-mv recorder was selected. The 0- to 50-µa meter of the PHS smokemeter required slightly different wiring for the TI 0- to 10-mv recorder. Instead of the external output terminals being wired in parallel with the 0- to 50-µa meter, they were wired in series with the meter and a 200-ohm, 1-watt resistance placed between the external output terminals. This resulted in a 10-mv output at 50-µa indication of the meter. Full-scale deflection of the microammeter (100-percent transmittance or 0-percent opacity) resulted in full-scale movement of the TI recorder.

The improved smokemeter recording system was applied initially to the Cummins NH-220 naturally aspirated, six-cylinder laboratory engine operated with a 300-hp water brake dynamometer. Shown on Table 7 of Appendix F are descriptive details of this engine and the calculations made to determine the lower engine speed of 1440 rpm employed during the (1) quasi-constant speed procedure. The smokemeter light beam was located 5-1/2 in. above the tip of the 4-in. diameter exhaust stack. The smoke levels read from the continuous traces obtained during the quasi-constant speed (1) procedures are listed on the bottom of Table 7 of Appendix F when engine speed decreased from 2200 to 1440 rpm, the average smoke reading decreased from 22 to 15-percent opacity. It was experimentally found that the best acceleration could be achieved by retaining the full power absorption characteristic in the water brake dynamometer at 1440 rpm, the last or lower speed, or the quasi-constant condition (1). After the 3-min idle, a full-rack acceleration of the engine was conducted. The engine speed almost immediately reached the 1440-rpm maximum power condition previously set. By releasing load (water), a smooth acceleration from 1440 rpm up to the rated speed was achieved. It is interesting to note that the high torque characteristic of this naturally aspirated engine was such to allow the engine to reach 1440 rpm in less than 2 sec. Unless external loading attachments such as large inertia flywheels, etc., are employed with this type of dynamometer, it may be difficult to obtain a smoother rate of acceleration. Acceleration of the engine, after it reached 1440 rpm, was not difficult to spread smoothly over the minimum 15-sec requirement of procedure (2). Approximately 18 sec were used to accelerate from 1440 to

2100 rpm, roughly 40 rpm per sec. Regardless of the rate of acceleration, the resultant smoke traces seemed to be the same in that there was basically a single small peak of approximately 18-percent opacity during the acceleration to fully loaded condition at 1440 rpm, followed by a drop-off in the smoke output, and then a slow climb back to 21- to 23-percent opacity corresponding to the 2000- to 2100-rpm range. The smoke readings obtained under this procedure fairly well repeated those obtained during the quasi-constant condition (1).

The dual trace technique was next applied to truck-tractors operated on the SwRI tandem axle chassis dynamometer. The first tractor investigated with the dual-pen technique was a Detroit Diesel 6-71 N powered tandem axle GMC cab-over tractor with ten-speed transmission. This tractor was the same unit investigated under the derating studies. This tractor, equipped with type 65N fuel injectors, develops 238 hp at 2100 rpm. Shown in Table 8 of Appendix F are descriptive data regarding this truck-tractor and engine. Also listed are the smoke measurements obtained during the quasi-constant speed (1) condition. This truck-tractor did not smoke appreciably under the constant speed type operation, the average smoke reading ranging from 2- to 4-percent opacity. This light, practically clear, smoke was slightly lighter than that reported in Section IV. No adjustments or maintenance to the engine had been performed since the tractor was utilized during May 1967. When accelerated to 2100 rpm, the rated speed of this engine, over approximately 19 to 20 sec, only a single momentary peak was recorded. Acceleration of the engine and vehicle was almost instantaneous to approximately 1550 rpm (26 mph in 8th gear), at which time the load setting in the chassis dynamometer was reduced to permit a smooth acceleration at open rack to rated speed of 2100 rpm. Without additional devices such as large inertia wheels or supplemental loading mechanisms, it may be difficult to make the acceleration rate more uniform and constant. The load, preset in the dynamometer, of maximum power at 1550 rpm remains in effect, and the loading schedule follows the normal "Q" curve up to 1550 rpm. The torque characteristic of the 6-71 N engine, however, resulted in an acceleration to this lower speed setting of the (1) procedure within 2 sec. The remaining 17 to 18 sec of the overall 19- to 20-sec acceleration were spread smoothly over the remainder of the acceleration by releasing load in the water brake. Vehicle speed and engine rpm were increased at approximately 1 mph per sec and 250 rpm per sec. The procedure appeared fairly repeatable, and these sets of experiments also indicated that the dual trace technique could be successfully employed. The maximum smoke during acceleration occurred at the initiation of the acceleration and resulted in a nearly instantaneous peak of approximately 25- to 30-percent opacity.

The next tractor operated on the chassis dynamometer was a naturally aspirated, single-axle Mack truck powered by a Mack END 673, six-cylinder, four-cycle engine which develops 187 hp at 2100 rpm. Descriptive data regarding this single-axle tractor are shown on Table 9 of Appendix F. According to the truck tachometer, the governed speed and the maximum speed was 2000 rpm, although the engine is rated at 2100 rpm. Rather than repair the tachometer or adjust the engine governor to remedy this situation, the tractor was operated in its "as-received" condition. Also shown on Table 9 are the smoke and power readings taken during the quasi-constant speed (1) procedure from 2000 rpm, 41 mph, down to 1400 rpm, 30 mph. The smoke measurements were less than 10-percent opacity under all conditions investigated during procedure (1). At the conclusion of the quasi-constant speed procedure, the full load was retained in the water during the 3-min idle period and during the consequent acceleration from idle speed of 550 rpm to the top speed of 2000 rpm of this tractor. The acceleration to 1400-rpm max power was quick, requiring approximately 2 sec to achieve. By releasing load, the remainder of the acceleration from 1400 rpm, 30 mph, to 2000 rpm, 41 mph, was fairly smoothly obtained. Repeatable accelerations were conducted which ranged from 23 to 24 sec in overall duration. A peak smoke of 13-percent opacity was obtained as the engine speed progressed through about 1900 rpm and decreased after the engine speed was maximum.

The next diesel rig evaluated was a tandem drive truck-tractor powered by a Mack ENDT 673C turbocharged version of the END 673 engine. Descriptive data regarding this truck-tractor and the ENDT 673C, rated at 250 hp at 2100 rpm, may be found in Table 10 of Appendix F. Operating in 12th gear of the Mack truck equipped with a triplex, fifteen-speed, Mack transmission, smoke increased as engine speed decreased, a characteristic similar to the turbocharged International Harvester V8 engine (Table 5, Appendix F) and the Caterpillar 1676 powered White Freightliner (Table 6, Appendix F). The smoke readings were not as great as with the Harvester and Caterpillar turbocharged engines and resulted in a maximum of around 20-percent opacity at the 1500-rpm end point of procedure (1). The smoke output increased substantially between about 1700 rpm, at which point the smoke readings were approximately 14-percent opacity, to the 20- to 22-percent readings obtained at 1500 rpm. Following the 3-min idle, a full-rack acceleration from idle speed, 500 rpm, to rated speed, 2100 rpm, was performed. The operating characteristic of this turbocharged Mack engine permitted a smoother acceleration rate than previously achieved with nonturbocharged engines. The turbocharged engine was not able to accelerate back to the 1500-rpm full load condition as quickly as the naturally aspirated engines. The overall duration of acceleration of approximately 21 sec was repeatedly obtained with little difficulty. During the first part of the acceleration, the smoke was a peak 55 percent and remained above 40 percent for about 2 to 3 sec. As the engine speed increased, the smoke decreased to 15-percent opacity at rated speed. Although the reasons are not known, this engine was not as powerful as the nonturbocharged version, although their basic power ratings are quite different. This may be due to fuel pump or fuel injector maladjustment or deterioration within the engine, such as valves, etc. In any event, this tractor was not pulling as well as it should, and it is possible that the smoke levels obtained with a similar tractor might produce more or less smoke. The smoke emissions would probably be more or less across the board and would not affect greatly the characteristic of where maximum smoke was produced.

A 1961 Mack B77, tandem drive axle truck-tractor powered by a Cummins NH-220 with turbocharger was operated on the chassis dynamometer next. The effect of turbocharging the NH-220 was to boost its rated output to 262 hp at 2100 rpm instead of the normal 220 hp at 2100 rpm. This tractor was equipped with a Mack quadraplex, twenty-speed transmission and two 4-in. diameter vertical exhaust stacks. The exhaust stacks were "Y" connected to the discharge from the muffler, and each handled basically the same amount of flow. Since the smoke appearance was adjudged to be about the same for each stack, measurements were obtained only on the right stack. Operating in 16th gear, the smoke readings were obtained as shown on Table 11 of Appendix F for the quasi-constant speed condition (1) throughout the speed range of 2300 to 1275 rpm. Maximum smoke, 11-percent, was obtained at 1500 rpm. Fairly smooth and repeatable accelerations were accomplished which required from 21 to 24 sec. Similar to the turbocharged Mack ENDT 673C, the acceleration rate was smoother than with the nonturbocharged vehicles. Immediately on full-rack acceleration, the smoke peaked at 43 to 45 percent and then dropped off quickly to approximately 15-percent opacity. This was followed, as the engine/vehicle continued to accelerate, by a gradual climb in smoke output back to about 38-percent opacity at 1500 rpm. Then, the smoke discharge decreased to about 13 percent at rated speed. This turbocharged tractor was adjudged to be in good operating condition and had satisfactory power output when compared to naturally aspirated NH-220 engines.

The last vehicle evaluated was a Ford H950 cab-over tractor powered by a Caterpillar Model 1673, four-cycle turbocharged engine, rated at 245 hp at 2200 rpm. The driveline consisted of a five-speed transmission and a three-speed axle resulting in fifteen forward speeds. Descriptive information regarding this tractor is contained on Table 12 of Appendix F. Operating in 13th gear, the smoke measurements were obtained throughout the 2300- to 1500-rpm speed range of interest under condition (1). As was the case with the Caterpillar 1676 turbocharged engine, the smoke output during the quasi-constant speed operating condition remained fairly light until the engine speed was reduced below 1700 rpm. At about 1600 to 1700 rpm, the smoke output became greater than 20-percent opacity and remained greater than 20 percent as the engine speed reduced to 1500 rpm. A full-rack acceleration from 550-rpm idle to rated speed was then accomplished after a 3-min idle. The acceleration, similar to the 1676 Model Caterpillar, produced an initial peak smoke of about 95-percent opacity which lasted for approximately 3 sec. The total time of this initial peak in excess of 40-percent opacity was about 7 to 9 sec in duration.

In summary, a variety of tractors and engine driveline configurations was studied using tentative PHS smoke evaluation procedures. Of necessity, the largest number of tests over the shortest period of time were obtained using rental or locally available truck-tractors powered by both turbocharged and naturally aspirated engines. These measurements resulted in two conclusions. The first was that the operating procedures can be utilized with chassis dynamometer and stationary dynamometer water brake type units with somewhat satisfactory results and repeatability. The acceleration from idle speed to rated speed was not, in the case of the naturally aspirated units, as smooth as that with the turbocharged engines. The other conclusion is the results may show that certain categories or types of equipment have a tendency to produce more smoke during one portion of the procedure than other types of equipment. This was apparent with some of the turbocharged engines during the acceleration from idle. As an alternative transient procedure, an acceleration from say max torque speed up to rated speed at a specified number of rpm per second may result in a procedure more realistic to field operation of diesel powered equipment. In conclusion, the limited number of tests and evaluations with the PHS procedures should be construed as only an indicator of the types and levels of smoke emissions from diesel powered tractors. As the smoke procedure is further refined and adjustments or modifications, if any, are added, a substantial number of tests should be obtained using both stationary and chassis dynamometer operated engines.

C. Evaluation of Gordine Diesel Electrostatic Precipitator

The intent of this evaluation was to determine the effectiveness of the Gordine Systems, Inc., electrostatic precipitator in removing particulate such as soot and smoke from diesel engine exhaust. On October 13, 1967, a prototype was provided for use with the Cummins NH-220, six-cylinder, four-cycle, naturally aspirated engine. The electrostatic precipitator device, prepared by Gordine under contract to PHS required the use of an external 0 to 30 kv at 6-ma current power supply. On November 22, 1967, an unsuccessful attempt was made to evaluate the prototype. This evaluation, planned with the test bed operated Cummins NH-220 engine under a variety of conditions resulted in premature failure of various components of the device. This occurred prior to being able to turn "on" the power supply for the electrostatic precipitator. Therefore, it was not possible to establish or investigate the potentialities of the device for removal or reduction of exhaust smoke.

Shown in Figure 40 is a schematic of the exhaust system apparatus and equipment used. The Cummins NH-220 exhaust was passed through a conventional truck-type cylindrical muffler and then through 6 ft of 4-in. diameter, flexible exhaust pipe. This was connected to a 10-ft length of 4-in. diameter straight exhaust pipe which was fitted with an adapter to flangeto the 3-3/4 × 5-3/8-in. rectangular inlet of the Gordine precipitator. After the exhaust passed through the Gordine unit, a suitable adapter was fabricated to flange back from the 6-1/2 × 7-3/4-in. rectangular outlet

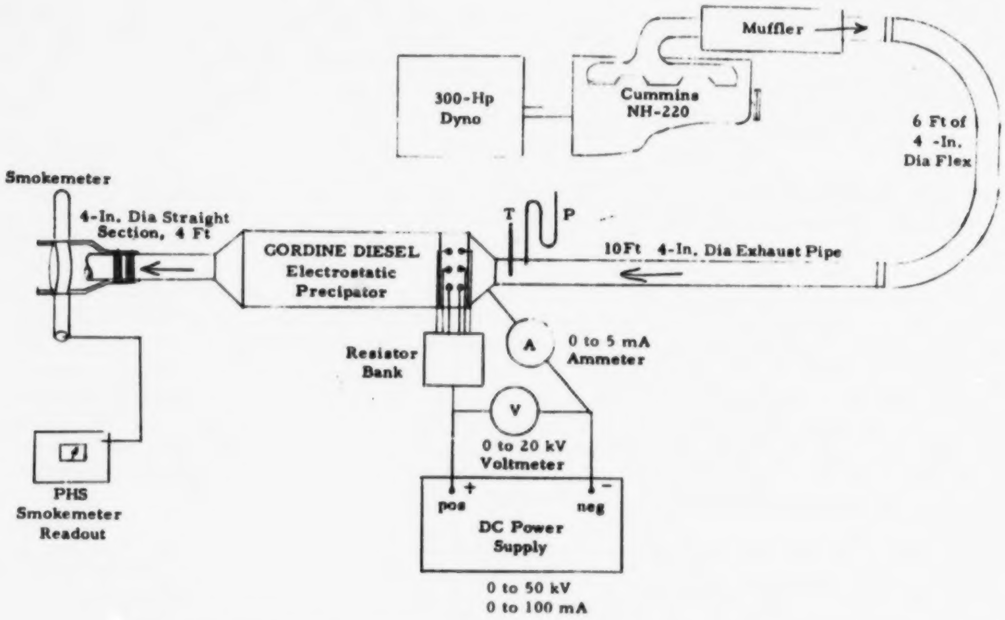


FIGURE 40. SCHEMATIC OF TEST APPARATUS AND ARRANGEMENT USED FOR EVALUATION OF THE GORDINE DIESEL EXHAUST PRECIPITATOR

to a 4-ft long, 4-in. diameter straightening section. The exhaust then passed through the PHS smokemeter mounted with the light beam 5-1/2 in. from the tip of the exhaust stack. A 0- to 50-kv power supply capable of 0 to 100 ma was used to supply the DC power required for the electrostatic precipitator. A 0- to 5-ma ammeter and 0- to 20-kv voltmeter were utilized to monitor the power supplied. Provisions were also made for measurement of the pressure and temperature of the exhaust at the device inlet.

Before the engine was started, a breakdown test was made of the electrostatic precipitator as requested in the September 8, 1967, letter from Mr. E. William Karches, Physical Research and Development Program, PHS. Shown on Table 40 is a listing of the current measurements at various input voltages. These measurements were obtained in still air and are shown along with the current measurements provided the Public Health Service. These measurements disagree slightly throughout the range of 7 to 13 kv. At 13 kv, however, periodic arcing was noticed between several electrode terminal posts and the case of the Gordine unit. Although, at 13 kv, breakdown was erratic, an increase to 14 kv resulted in continuous discharge between the terminal post and the precipitator housing. It was uncertain whether periodic or continuous discharge was occurring within the precipitator.

After the measurements on Table 40 were obtained, an attempt was made to evaluate the performance of the Gordine unit under actual diesel engine exhaust conditions. A number of failures occurred during the approximately 5 min of engine operation with the Gordine unit in the exhaust of the Cummins NH-220, six-cylinder truck engine. Some of these failures can be seen in Figure 41. After about 1 to 2 min of operation at a moderate engine speed of 1500 to 1700 rpm and low load, one of the six electrode wires became detached from within the precipitator unit and fell out. This wire, as well as a small insulator, is shown laying on top of the precipitator housing near the hole which

TABLE 40. DC POWER INPUT TO GORDINE DIESEL EXHAUST ELECTROSTATIC PRECIPITATOR

Note: The SwRI measurements were obtained in still air prior to operation with engine. The PHS measurements are from letter of September 8, 1967, from William E. Karches, Physical Research and Development Program, PHS.

kv	PHS Current, ma	SwRI Current, ma
7	0.04	0.02
8	0.24	0.08
9	0.65	0.30
10	1.1	0.60
11	1.8	1.0
12	2.2	1.6
13	2.8	2.3*
14	3.3	†
15	4.0	†

---

*Periodic arcing between input terminal post and exhaust pipe mounting flange on case.

†Continuous discharge between terminal post and flange on DEP housing.

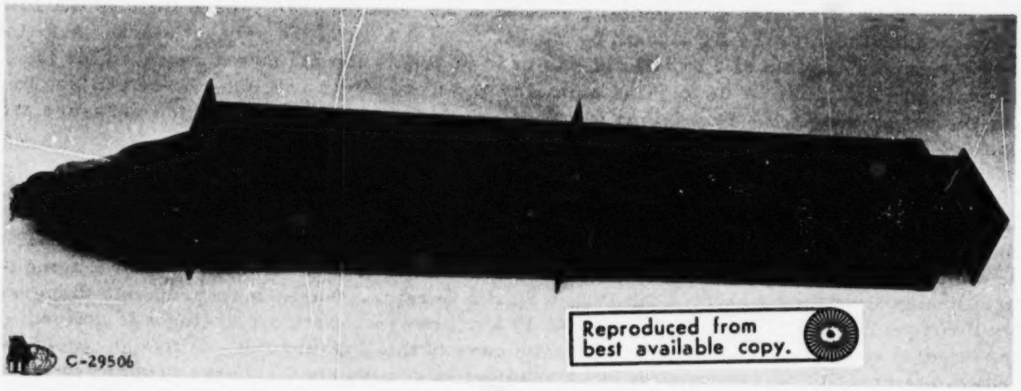


FIGURE 41. GORDINE DIESEL EXHAUST ELECTROSTATIC PRECIPITATOR AFTER 5 MIN OF OPERATION WITH A MULTI-CYLINDER TRUCK DIESEL EXHAUST

(Flow Is from Right to Left)

was accoustically caused in the casing of the precipitator shown in Figure 41. Notice the black soot at some of the seams of the case which indicates the magnitude of the failure of the case and housing seams during the 5 min of operation. Under no circumstances did the inlet gas temperature exceed 800°F. On dismantling the system from the hookup pipe, the copper collector screening wire was found partially blown out of the exit end of the precipitator device. It was found as shown on the left side of the photograph. On November 27, 1967, the Project Officer was informed of the difficulties experienced. A brief report was forwarded to PHS, dated November 30, 1967, including a photograph and a small portion of the case which chunked out of the device. The material of construction was galvanized sheet metal of fairly thin gauge. Normal practice in the manufacture of muffler equipment is to conform to generally a circular cross section in which the wall thickness is maintained at about 1/16 in. or more, depending on the diameter of the device. These comments regarding the failure, as well as the current measurements shown on Table 40, were relayed by telephone to Mr. Anthony J. Farina, a representative of Gordine Systems, Inc. As requested by the Project Officer, the prototype electrostatic precipitator was shipped to Gordine for inspection.

D. Odor, Smoke, and Exhaust Emissions from a Flxible Coach Powered by a Cummins Four-Cycle Engine

The objective of this item was to obtain odor, smoke, and exhaust emissions base line data from a single Flxible Coach powered by a Cummins four-cycle engine. The approach was to obtain base line data under equivalent operating conditions utilized during similar investigations with GM municipal buses powered by two-cycle engines.

1. Preparations

On December 12, 1967, a fifty-one-passenger, 1966 Flxible Transit Coach, Model 111 CC-C1-1 was delivered to the Vehicle Emissions Research Laboratory by a representative of the Flxible Company, Loudonville, Ohio. This vehicle was powered by a four-cycle, naturally aspirated Cummins V8, 265-hp diesel engine custom derated to deliver 210 hp at 2600 rpm and was similar to those described in experimental test operation in the Southern California Rapid Transit System (Ref. 19). For a brief description of this vehicle, please refer to Table 13, Appendix F. Shown on Figure 42 is a front view of the bus on the chassis dynamometer. Adjacent to the driver are the usual vehicle power and speed indicators, as well as a dual pen TI strip chart recorder employed to record vehicle speed and engine speed simultaneously. Below the dual pen recorder and not seen in the photograph is a Hewlett-Packard electronic counter which

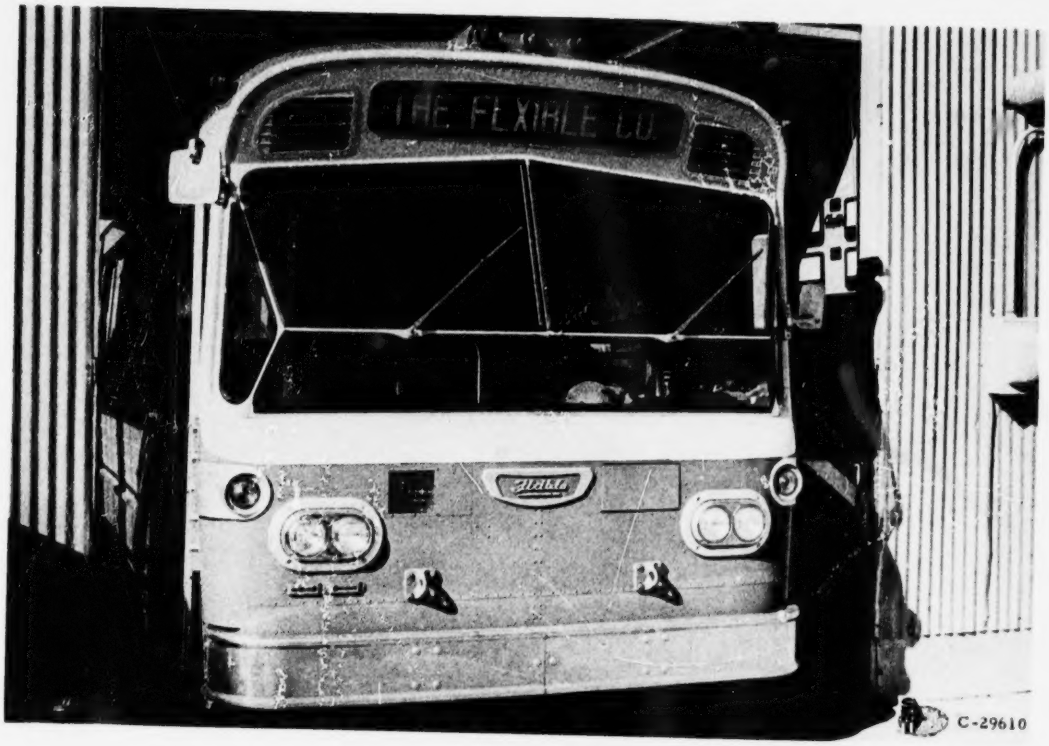
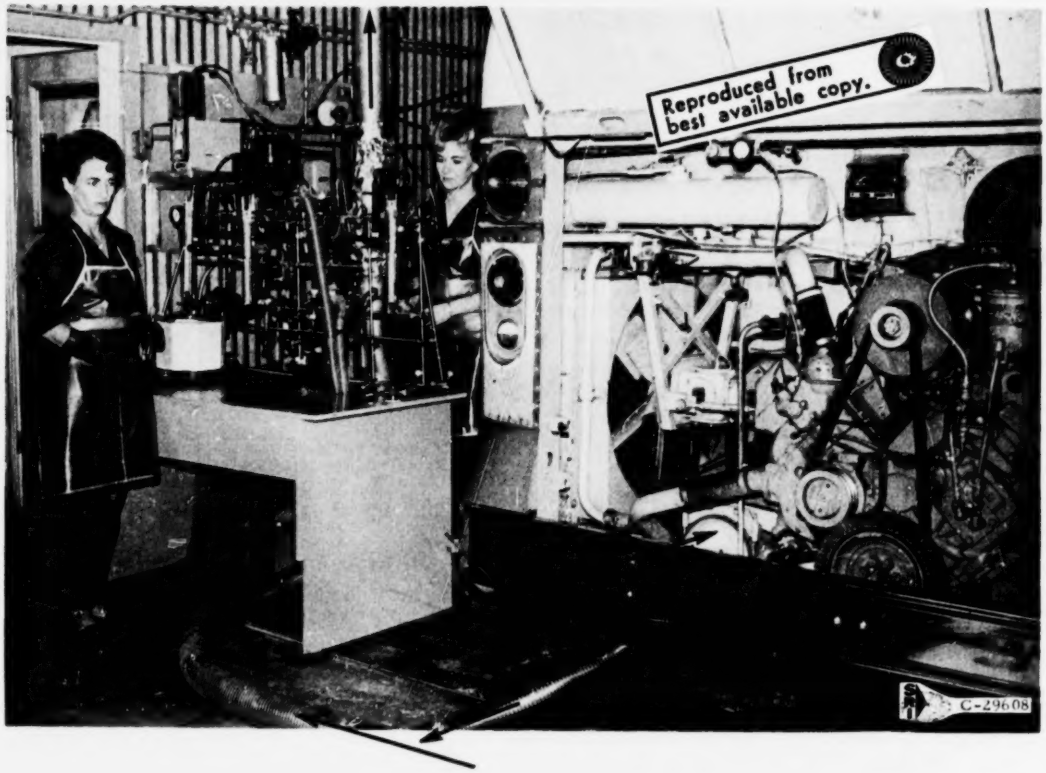


FIGURE 42. FLXIBLE TRANSIT COACH ON TEST IN HIGH BAY CHASSIS DYNAMOMETER AREA OF VEHICLE EMISSIONS RESEARCH LABORATORY

continuously indicates engine speed. Since the Flxible Coach is slightly longer than the usual forty-five-passenger municipal buses evaluated, the front protruded about 12 in. beyond the front door of the high bay.

Shown in Figure 43 is a rear view of this unit with the engine compartment door up. The V-8 Cummins, 265-hp four-cycle engine is mounted with the crankshaft parallel with the longitudinal axis of the vehicle. The right-angle gear drive arrangement for the cooling fan is also shown in this photograph. An arrow on the photograph points to the muffler which was installed directly below the right bank of the engine. This muffler is close connected to the exhaust of the four cylinders comprising the right bank. A similar muffler, not shown, is located below the left bank. After discussions with the Project Officer, it was agreed to connect the two 3-in. diameter exhaust pipe extensions from each muffler into a common 4-in. diameter manifold shown in the long arrow at the bottom of the photograph. The combined exhaust was then directed through the central laboratory exhaust stack shown to the left of the bus by the vertical arrow. Between the two laboratory technicians is the central laboratory stack from which samples were obtained for dilution and analysis by the odor panel, as well as for wet chemical measurement of acrolein, total aldehydes, formaldehyde, oxides of nitrogen and SO_2. Samples were also obtained from this stack via an ice bath condenser filter system for CO and CO_2 analysis by nondispersive infrared. In addition to the fabrication of the special 4-in. manifold, the laboratory supply of number 2 diesel fuel, SwRI Code EM-29-F, was connected to the engine. Available exhaust manifold pressure taps were utilized to obtain engine backpressure measurements in inches of water. The special tachometer drive for use with the TI recorder and Hewlett-Packard counter was also installed. Aside from these preparations, no modifications, changes, or adjustments were performed on the engine or vehicle. The number 2 diesel fuel was selected on the basis of the manufacturer's and Project Officer's recommendation. For a description of the number 2 fuel employed, SwRI Code EM-29-F, please see Table 2, Section II.



Reproduced from best available copy.

FIGURE 43. REAR VIEW OF FLXIBLE COACH POWERED BY CUMMINS V8-265, FOUR-CYCLE ENGINE

2. Results

The results of initial familiarization with this type of vehicle/engine combination revealed the operating characteristics were similar to those obtained with two-cycle powered, two-speed municipal buses. Vehicle performance, with the Dana two-speed automatic transmission, resulted in vehicle upshift at 22 to 23 mph and downshift at 19 mph. The free idle of the engine was 615 rpm, and, when shifted into gear, this idle speed dropped to 585 rpm. The maximum no-load engine rpm was 2660. Although field data were not obtained regarding the operating modes, etc., which produce significant levels of odor and smoke, it seemed reasonable, for this limited study, to employ the existing procedures and dilution level to obtain data on a comparable basis. The Flxible Coach discharged the exhaust horizontally at approximately the same height above the road as previously tested units, although at slightly different positions relative to the center line of the vehicle. The exhaust pipes from the Flxible Coach are directed straight back at approximately 2-1/2 ft on either side of the center line of the vehicle. As may be seen in Figure 42, a small exhaust pipe is located at the left rear corner under the bumper. This exhaust pipe served the Perkins four-cycle engine used to power the air-conditioning system for the vehicle. The exhaust from this separately operated and controlled "air conditioning engine" was not evaluated.

The complete results of the odor, smoke and exhaust emission measurements obtained with the Flxible Coach are included as Tables 14 through 29 of Appendix F. The odor evaluation conditions, listed in Table 14, were the same as those developed during Part I. Detailed procedures may be found on Tables 15 through 18 of Appendix F. Shown on Table 41 of the text (Table 23 of Appendix F) is an overall summary of the odor evaluations performed. A 4-day period was devoted to gaining odor data. In random order on successive days beginning December 19 and ending

TABLE 41. OVERALL SUMMARY OF ODOR EVALUATIONS FROM FLXIBLE BUS

Vehicle: Flxible Coach 111 CC-C1-1
Engine: Cummins V8-265[1]
Date: December 19-22, 1967

Operating Conditions: See Table 14 of Appendix F
Fuel: EM-29-F (No. 2 diesel)

Operating Condition[2]	Date Evaluated	Average Four-Run Panel Responses "D" Composite	"B" Burnt	"O" Oily	"A" Aromatic	"P" Pungent
I	12/19/67	5.9	1.3	1.4	0.9	0.8
	12/20/67	4.8	1.4	1.1	0.8	0.5
	12/21/67	5.1	1.4	1.1	0.9	1.0
	12/22/67	5.2	1.4	1.0	0.9	0.8
	4-day average	5.2	1.4	1.2	0.9	0.8
II	12/19/67	5.4	1.5	1.1	0.7	0.9
	12/20/67	5.1	1.5	1.2	0.7	0.8
	12/21/67	4.7	1.3	1.0	0.6	0.8
	12/22/67	5.5	1.7	1.3	0.8	1.1
	4-day average	5.2	1.5	1.2	0.7	0.9
III	12/19/67	4.4	1.1	1.0	0.7	0.6
	12/20/67	4.8	1.4	1.1	0.7	0.6
	12/21/67	4.1	1.0	0.8	0.6	0.6
	12/22/67	4.5	1.2	1.0	0.8	0.6
	4-day average	4.5	1.2	1.0	0.7	0.6
IV	12/19/67	6.3	1.9	1.6	0.8	1.0
	12/20/67	6.0	1.9	1.5	0.9	1.0
	12/21/67	5.9	1.9	1.5	0.9	1.2
	12/22/67	6.4	2.0	1.7	1.0	1.3
	4-day average	6.2	1.9	1.6	0.9	1.1
V	12/19/67	5.8	1.7	1.4	0.9	1.0
	12/20/67	5.1	1.5	1.1	1.0	0.8
	12/21/67	5.9	1.7	1.3	1.1	0.9
	12/22/67	5.7	1.7	1.4	0.9	1.1
	4-day average	5.6	1.7	1.3	1.0	1.0

---

[1] Custom derated to 210 hp at 2600 rpm.

[2]
I Constant Speed, 20 mph
II Constant Speed, 40 mph
III Idle after 30-mph, 40-hp cruise
IV Acceleration after 1-min idle
V Deceleration from 40-mph, 40-hp cruise

December 22, 1967, twenty-four runs, five conditions in quadruplicate plus four blanks, were presented. From Table 41, the "D" composite rating appeared greater under most operating conditions during the first day of the 4-day sequence. The highest odor ratings were obtained consistently for condition IV, the full-rack acceleration after a 60-sec idle. The next highest rating occurred during condition V, the deceleration after a 40-mph cruise. These transient conditions were followed in order of importance by the two cruise conditions at 20 and 40 mph. The weakest odor measured consistently occurred during the idle, condition III. The "B" rating appeared to follow this trend as did the "O" and "P" ratings. The data in Table 41 were summarized from detailed information contained in Tables 24 through 27 in Appendix F. Tables 24 and 24A-24E cover the odor ratings for the first day of evaluation. Likewise, Tables 25 and 25A-25E and 26A-26E, and 27 and 27A-27E contain the detailed results for the second, third, and fourth day.

The odor panelists were also asked to comment on the general character and problems encountered. These comments were solicited at the end of each day's evaluation and summarized. Briefly, the odor panel found the 100:1 diluted odor difficult to rate in that the odors seemed sweet or sour and at times both sweet and sour. This was in contrast with "B" rated as most obvious. Although "B" was rated as most obvious, the exhaust did not possess the intense burnt and heavy smoky character normally associated with "B"--most obvious--ratings. The next most obvious odor was the "O" oily quality. The "A" aromatic-aldehydic and "P" pungent quality ratings appeared to be the least most obvious but in no particular order. Occasionally a kerosene type odor indicative of unburned number 1 diesel fuel was noted, particularly during the idle-acceleration condition. The panel members were unanimous in their appraisal of the bus exhaust being of a mild nature with a more aromatic odor quality than normally found.

Base line smoke data were also obtained using measurement conditions and procedures described on Tables 19 through 21 of Appendix F. Listed on Table 42 of the text is an overall summary of the smoke measurements obtained with the Flxible Coach. The smoke readings were obtained under constant speed operating conditions ranging from 20 to 60 mph with corresponding engine speeds from 855 to 2330 rpm. Operating at open-rack maximum power output, the average smoke readings are listed in percent opacity for both the left bank and right bank of the engine. At speeds less than 50 mph, 2100 rpm, and 119 vehicle hp, the smoke readings were less than 10-percent opacity. At normal speeds encountered in urban and suburban nonfreeway driving, the smoke was substantially less than 10 percent ranging from 3 to 6 percent. The highest smoke readings, under constant speed conditions, were consistently obtained with the left bank of the engine and reached a maximum of 13-percent opacity at 60 mph, 2330 rpm, and 123 hp.

Shown on the bottom half of Table 42 are the results of the idle-acceleration condition, obtained under open-rack engine acceleration after a 1-min duration idle. In an attempt to map the smoke emissions during this transient condition, a number of road load conditions were simulated by presetting in the water brake dynamometer at 30-mph fixed power absorption of 0, 15, 30, 45, and 60 hp. With each of these preset dynamometer conditions, the vehicle output followed the characteristic "q" road load feature throughout the speed range operated. During the idle-acceleration experiments conducted with similar vehicles powered by two-cycle engines, two instances during the acceleration were of interest from the standpoint of maximum smoke production. They were the initial acceleration after the prolonged idle and immediately after the upshift from low to drive range of the transmission. Engine start was also felt of interest, although this type of condition does not recur in normal use. Summarized on the lower part of Table 42 are the smoke measurements at engine start, during initial acceleration and after upshift which indicate that nearly negligible smoke was produced. The readings were less than 5-percent opacity during the initial acceleration and after upshift.

Please refer to Tables 28 and 29 of Appendix F for detailed smoke readings obtained with the Flxible coach. Also shown on Table 42 are the end-of-acceleration vehicle speed and power. The procedure was to accelerate to 50 mph or as close to 50 mph as possible. With 30 hp preset in the dynamometer at 30 mph, the maximum speed obtainable was 50 mph with 120-hp output at the rear wheels. When 45 and 60 hp were preset in the dynamometer at 30 mph, the end of acceleration speeds were reduced to 43 mph (112 hp) and 37 mph (100 hp), respectively. Figures 1, 2, and 3 of Appendix F are continuous recordings of vehicle speed, engine speed, and smoke in percent opacity for a road load condition of 0, 30, and 60 hp preset at 30 mph and retained throughout the acceleration. Regardless of the road load power condition, the continuous trace recording was somewhat less than 10-percent opacity. As the road load condition increased from 0 to 60 hp, an apparent "flat spot" in the acceleration rate (vehicle speed, mph, per unit of time) became more procounced. This "flat spot" is shown immediately after upshift. It was greater in duration at 60-hp road load than at 30 hp, and the 30-hp "flat spot" was greater than at 0-hp road load. The reason for this essentially zero acceleration rate is not known at this time.

Other emissions, including CO, CO_2, acrolein, formaldehyde, total aliphatic aldehydes, NO_x, SO_2, and O_2, were measured under a number of operating conditions. These measurements were obtained using procedures for sampling and analysis described on Table 22 of Appendix F,

TABLE 42. SUMMARY OF SMOKE MEASUREMENTS OBTAINED WITH FLXIBLE COACH

Vehicle: Flxible Coach 111 CC-C1-1
Engine: Cummins V8-265(1)
Date: December 28, 1967

Operating Conditions: See Tables 20 and 21 in Appendix F
Fuel: EM-29-F (No. 2 diesel)

Constant Speed Average Results, all at open rack, maximum power.

Operating Condition	Vehicle Speed(2), mph	Engine Speed, rpm	Vehicle Output, hp, obs	PHS Smoke Reading, % Opacity (Average)	
				Left Bank	Right Bank
A	20	855	60	3	2
B	25	1050	67	3	2
C	30	1275	80	4	2.5
D	35	1485	92	5	3.5
E	40	1700	105	6	3.5
F	45	1900	115	7	5
G	50	2100	119	9	6.5
H	55	2225	122	12	7.5
I	60	2330	123	13	8

Idle-Acceleration (Condition J) average results, open rack.

Road Load(2), hp	PHS Smoke Reading, % Opacity(3) (Max Average)			End of Accel	
	Engine Start	Initial Accel	Upshift	Speed, mph	Power, hp
0	3	2	3	50	0
15	4	3	3	50	58
30	5	2	4	50 (Max)	120
45	7	2	4	43 (Max)	112
60	6	3	3	37 (Max)	100

---

(1) Custom derated to 210 hp at 2600 rpm.

(2) Preset in dynamometer at 30 mph and retained during acceleration.

(3) Measured from left bank of engine--exhaust system.

identical to those used during the catalytic muffler evaluations. For additional base line data with the Flxible bus, the operating conditions were expanded to include a 30-mph, 40-hp cruise as well as a 25- and 50-mph cruise at no load and maximum power output. Shown on Table 43 of the text is a summary of the "as-measured" average exhaust emissions measured from the Flxible Coach. Conditions 1 through 4, the 20-, 30-, and 40-mph cruises at 40 hp and the idle after the 30-mph cruise, respectively, were conducted on December 27 in numerical order four times. Conditions 5

TABLE 43. SUMMARY OF "AS-MEASURED" AVERAGE FLXIBLE COACH EXHAUST EMISSIONS MEASUREMENTS

Vehicle: Flxible Coach 111 CC-C1-1
Engine: Cummins V8-265(1)
Date: December 27 & 29, 1967

Operating Conditions: See Table 22, Appendix F
Fuel: EM-29-F (No. 2 diesel)

Operating Condition	Vehicle Speed, mph	Vehicle Load, Hp	CO, ppm	CO_2, %	Acrolein, ppm	Form-aldehyde, ppm	Aliphatic Aldehydes, ppm(2)	NO_x, ppm(3)	SO_2, ppm	O_2, %	Adjusting Factor(4)
1	20	40	190	7.15	0.93	1.62	9.70	1918	6.50	11.06	2.09
2	30	40	115	5.4	0.90	1.44	8.64	1156	5.85	13.31	2.76
3	40	40	100	4.95	0.93	1.44	8.64	714	5.29	14.13	3.02
4	0	0	75	1.85	0.74	1.80	8.64	258	2.46	18.0	8.11
5	25	0	80	2.3	1.51	3.31	9.16	484	3.82	17.38	6.5
6	25	70	1040	10.0	1.33	5.19	8.98	2723	10.15	6.75	1.49
7	50	0	100	3.15	1.24	3.23	9.55	469	4.80	16.31	4.76
8	50	130	980	8.6	4.39	12.88	15.56	1432	9.67	8.69	1.73

(1) Custom derated to 210 hp at 2600 rpm.
(2) Total as ppm formaldehyde.
(3) Total as ppm NO_2.
(4) Adjusted average values based on 15 divided by the percent (CO and CO_2) in the exhaust using "as-measured" average CO and CO_2 measurements.

through 8, the 25-mph no load, 25-mph full load (70 hp), the 50-mph no load, the 50-mph full load (130 hp), were likewise conducted on December 29, 1967. CO remained low, less than 200 ppm, except during maximum power at 25- and 50-mph cruise which resulted in 1040 and 980 ppm, respectively. Acrolein remained low except for the 50-mph, 130-hp cruise when acrolein, normally less than 1.5 ppm, increased to 4.39 ppm. Formaldehyde and total aliphatic aldehydes likewise remained fairly low except during the 50-mph maximum power condition. Formaldehyde, which was generally less than about 5 ppm, increased to 12.88, and the total aldehydes, which generally averaged about 9 ppm, increased up to 15.56 ppm during this same condition. Oxides of nitrogen were greatest during conditions 1, 2, 6, and 8, particularly conditions 1 and 6. These conditions resulted in "as-measured" NO_x of greater than 1000-ppm NO_2. The highest value was found during the 25-mph maximum power condition, condition 6, in which the NO_x values averaged 2723-ppm NO_2. The next highest NO_x value (1918-ppm NO_2) was found under condition 1, the 20-mph, 40-hp cruise. SO_2 values, shown next, ranged from 2.46 ppm during the idle condition to 10.15 at the 25-mph, 70-hp condition. It appears that SO_2 increased as engine power and fuel delivery increased and as possibly a direct function of the sulfur in the fuel.

To permit comparison of the emissions measurements obtained with the Flxible Coach powered by a four-cycle engine to other diesel powered vehicles and, if desired, gasoline vehicles, an adjusting factor is listed in the last column of Table 43. The adjusting factor was computed by dividing 15 by the percent CO plus CO_2 in the exhaust to adjust for the inherent air dilution in the exhaust of diesel type engines. The adjusting factors ranged from 2.09 to 3.02 for the 20-, 30-, and 40-mph, 40-hp cruises. During idle and other operating conditions of no load, the adjusting factor increased to 8.11 (idle), 6.5 (25-mph no load cruise), and 4.76 (50-mph no load). When the engine was operated at maximum power, the factor decreased to 1.49 for the 25-mph, 70-hp condition and 1.73 for the 50-mph, 130-hp cruise. In summary, emissions were obtained under a variety of operating conditions, speeds, and loads, and representative data determined. When the "as-measured" data are multiplied by the adjusting factor, the resulting normalized emissions may be compared with similarly determined diesel and gasoline emissions.

3. Summary

Representative and typical odor, smoke, and exhaust emissions were obtained with a Flxible Coach powered by a Cummins V8, 265-hp, four-cycle engine. The similiarities of this four-cycle powered, two-speed transmission, municipal bus to previously evaluated municipal buses allow a direct comparison of odor and smoke under identical conditions. A total of 4 consecutive days was devoted to the measurement of odor by the ten-person panel under vehicle speeds and loads, and the 100:1 exhaust dilution level established during Part I as typical of diesel powered municipal buses. Smoke measurements were obtained under an expanded number of constant speed and idle-acceleration conditions to fully investigate the smoke production tendency of this engine/vehicle combination. Exhaust emissions were obtained under a variety of vehicle cruise speeds at several different power levels. The odor measurements were somewhat different in odor quality from previous experience, even though the ratings ranged from "D"-4 to "D"-6, with an overall average of about "D"-5.2. The difference in character was difficult to assess with the PHS Q/I kit as the "B" quality continued to be most obvious, even though of low intensity and noticeably mild. The four-cycle powered Flxible Coach emitted low, almost negligible, levels of exhaust smoke. Exhaust emissions including CO, CO_2, acrolein, formaldehyde, aldehydes, NO_x, SO_2, and O_2 were obtained for eight conditions and were presented on an "as-measured" basis. In conclusion, a representative amount of base line data was acquired with the four-cycle powered Flxible Coach under operating conditions and procedures that permit direct comparison to previously obtained diesel powered vehicle data included in this as well as the Part I Final Report.

X. DATA ANALYSIS AND STATISTICAL SUPPORT

The objective of this portion of the program was to provide statistical analysis of experimental data generated under this program. As the program objectives became better defined, it became evident that statistical analysis would be required mostly for the mass of data generated during the evaluation of catalytic mufflers. Although the statistical techniques selected and described in this section could have been applied to the results obtained from studies of engine derating, Jacobs brake, and DEOX, it was agreed with the Project Officer that statistical analyses would not be conducted at this time. This was justified on the basis of the obvious lack of effect that any of the technique exerted on the resulting exhaust odor. Not only were the odor ratings basically the same with or without these techniques but the ratings were adjudged light and inherently subject to more spread and variability than panel ratings under stronger odor producing conditions. Consequently, statistical analysis for difference, under such circumstances, was felt superfluous.

A number of discussions were held with the SwRI computation section to establish methods of analysis and statistical treatment of the volume of data that was generated during the catalytic muffler evaluations. The mathematician was requested to determine, using the best statistical techniques available, if the odor, smoke and selected analyses made with each catalytic versus stock muffler were statistically different. Once these differences were established statistically, interpretation was required as to whether they represented an improvement. The performance of the catalytic relative to the stock muffler was ascertained by four general measurement categories including smoke, odor, exhaust emissions, and selected physical measurements. Each of these broad categories of measured variables was considered as to whether a statistical analysis was justified and actually indicated anything that an engineering analysis would not. In the case of smoke measurements, it was determined that the data obtained in triplicate by this technique could best be interpreted by simply comparing the average result obtained. The spread or variability in measurements was such to insure the validity of this approach.

The next block of data used as an indicator of the performance of the catalytic muffler was that of the odor measurements obtained by the ten-person odor panel using the Q/I measurement system. Statistical interpretation of the subjective, qualitative, quantitative analyses and evaluations performed by the trained odor panel was the most difficult to reconcile area as regards interpretation and data handling.

A. Treatment of Odor Panel Data

For purposes of Part I, the odor panel was treated as a single entity, and the responses of the individual members were handled by arithmetic techniques. Although the individual panelist response and response distribution were of basic importance, the technique employed was to average the ten-person response for the "D," "B," "O," "A," and "P." This meant that for each run of each condition, the ten responses for the "D" were arithmetically averaged. The same procedure was used for each of the four qualities which comprised the diesel composite, resulting in five overall average responses for that particular run. For purposes of evaluating the municipal bus powered by a two-cycle engine, five different conditions were investigated, and these conditions were presented to the panel at random in quadruplicate. The four-run responses were then accumulated and grouped by operating conditions and another average obtained for the four runs for the "D," "B," "O," "A," and "P" responses. For each day of vehicle operation, the individual panel responses were averaged twice in order to obtain an indication of the quality and intensity profile of the exhaust.

As indicated in the Part I Final Report, the advisability of the aforementioned data reduction system was uncertain in that it may not have been the optimum. In an attempt to design a potentially better method, the PHS Q/I odor characterization method and procedures used in analyzing dilute samples of diesel exhaust were restudied. The method of subjective analysis, the odor standards on which these analyses are based, and the procedure and techniques made use of by other knowledgeable researchers and statisticians in odor measurement and analysis were also reviewed. One argument for different data treatment was that averaging of the panel response was not quite valid because the odor kit is constructed of materials whose concentrations do not follow a linear relationship. For example, the "D" diesel composite intensity series runs from bottles Nos. 1 to 12, each bottle being twice as strong as the preceding bottle (a bottle No. 6 is twice as strong in concentration as a bottle No. 5). To complicate things further, the concentrations of some of the quality standards which comprise the overall diesel standard are not on a predictable relationship similar to "D" since adjustments had to be made for diluent interferences and for other practical reasons. In essence, the averaging technique says that the average of a perceived bottle No. 6 and a bottle No. 8 is a bottle No. 7, but, from the bottle contents concentration standpoint, this is not true.

After reviewing a recent Scott Final Report (Ref. 6) and particularly Dr. Katti's statistical analysis of the odor data, conversations with SwRI staff experts, a PHS statistician, and review of industry comments regarding statistical analysis techniques for use with the PHS Q/I kit responses, an inquiry was made to Dr. Amos Turk, developer of the PHS Q/I kit (Ref. 3). When fully informed of the magnitude and importance of the problem, Dr. Turk reported in his letter of October 4, 1967, that:

> "The perceived intensity of a stimulus is said to be directly proportional to the logarithm of the magnitude of the stimulus (Weber-Fechner Law) or to a power function of the magnitude of the stimulus (S. S. Stevens). Whatever the relationship may be for intensity vs. concentration of diesel exhaust, the series of reference standards in the diesel kit were designed to present equal increments of perceived odor intensity to the panel member. In some cases the concentration series show discontinuities; these are designed to compensate for solvent effects and to preserve the linearity of psychological magnitude. In averaging these values by the arithmetic mean, we are averaging psychological magnitudes, not concentrations. We therefore recommend that the arithmetic mean be used.
>
> "An analogy is the pH scale of acidity. One cannot, of course, use an arithmetic mean of pH values to obtain an average pH of several solutions. But if it were determined that, for some specific substance (like citric acid), over some particular pH range, the sourness varied directly with the pH value, then it would be reasonable to use a pH reference scale to score sourness responses of different people and to average these values."

As a result of Dr. Turk's recommendation and justification for the use of the arithmetic mean as the only plausible method of grouping and interpreting the odor panel responses, it was determined, with the knowledge and consent of the Project Officer and PHS statistician that the averaging method of treating the entire panel as a single entity would be continued. This method of panel response treatment would be used not only for reporting the odor panel responses and subjective measurements, but in consequent statistical analysis.

B. Selection of "U" Statistic to Determine Difference

So far, a brief review has been furnished describing the methods by which the responses from the ten-person odor panel have been reduced to a usable form. In addition, the justification for initially handling the odor panel data by simple arithmetic averaging procedures was justified and affirmed for continuing use. The next step was to consider all possible statistical methods which could be employed to determine differences in odor measurements. The standard "T" test for the determination of statistical difference between two populations of data was considered initially. Although the "T" test could be applied for the case in which the odor data and chemical measurements data were obtained in quadruplicate, this may not be a desirable statistical treatment method. This conclusion was reached by both the SwRI and PHS statisticians. The reasoning was that the basis for the "T" test is the need for the data to be from normally distributed populations. With a population of only four data points, one cannot be assured that the data points do not represent end points of the distribution. Another parametric type test, such as the "F" test, was considered, but, at the advice of the PHS statistician, it was agreed that an appropriate nonparametric type of analysis should be employed if at all possible. After a review of the various nonparametric tests available and applicable, it was determined that the "U" test (Mann-Whitney Test) seemed to be most appropriate and useful. The "U" test may be described by the following expression:

$$U_s = mn + \frac{m(m+1)}{2} - T$$

where

m - number of readings in the smaller set

n - number of readings in the larger set

for

$m \neq n$ - T is the sum of the relative rankings of the smaller set

$M = n$ - T is the sum of the set which gives the larger relative rankings.

The procedure was to list in order of magnitude or rank beginning with the lowest result and ending with the highest result. Each reading used in the relative ranking was the average panel response for each of the eight runs made under each operating condition (four with the catalytic and four with the stock muffler installed). To explain, the following example is shown for a typical set of odor measurements.

Given is a set of actual "D" responses for a 20-mph cruise.

Catalytic	Stock
6.8	4.4
6.4	6.3
6.1	4.4
6.0	5.8

Step 1: Since the number of responses are the same for both the catalytic and stock muffler, designate the catalytic muffler data as set "n" and stock muffler data as set "m."

Step 2: The four values of set "m" and the four values of set "n" are ranked according to the least intense response first to the most intense response in the eight position.

Relative Ranking	"D" Response
1	4.4 - Stock
2	4.4 - Stock
3	5.8 - Stock
4	6.0 - Catalytic
5	6.1 - Catalytic
6	6.3 - Stock
7	6.4 - Catalytic
8	6.8 - Catalytic

Step 3: Since the set "m" and "n" are of equal number, the largest sum (T) of the relative rankings will be used to compute U_s.

Set "m" (Stock)	Set "n" (Catalytic)
1	4
2	5
3	7
6	8
12	24

Step 4: Evaluating the equation for the "U_s" statistic gives a U_s value of two. By definition of the "U" statistic with the sets $m = n = 4$, the test does show a statistical difference:

$$U_s = mn + \frac{m(m+1)}{2} - T$$

$$U_s = 26 - 24$$

$$U_s = 2$$

For purposes of determining whether the catalytic muffler is statistically different from the stock muffler, it was determined by SwRI statisticians that the "U_s" statistic should be 0 to 2, where m equals n; that is, the number of repeat measurements is the same for the catalytic and non-catalytic sets of data. Where an uneven number of data have been obtained such that m does not equal the n, the most common occurrence being m equal to 3 and n equal to 4, the statistical difference has beeen placed where the "U_s" statistic is equal to 0 to 1.

To determine if the various exhaust emissions were statistically different, the "U" statistical analysis was recommended. To permit sampling, exhaust emissions measurements were limited to steady state conditions. These conditions were the same as used in odor measurements, namely, the 20- and 40-mph cruise, and the idle after a 30-mph cruise, and were conducted four times. The results of the "U" test must be viewed with some caution and insight as to the method of measurement, etc. For example, the "U" test will show a statistical difference for a set of readings of 150-, 150-, 151-, 149-ppm CO and a set of readings of 155-, 156-, 154-, 154-ppm CO. When these two sets of readings are considered from a practical standpoint, including limitations of the NDIR, sampling, etc., these two sets of readings are not different but are essentially the same and should be judged accordingly. Therefore, it is with this precaution of using common sense and engineering judgment that the statistical results obtained from the "U" test should be viewed. The "U" test only says that, according to the data, there is or is not a statistical difference. Interpretation of this result must then be made, particularly for the odor panel results. It is difficult to assess whether a statistical difference in odor measurements was actually a significant difference. In addition, it is difficult to say at the current level of understanding that a panel change of a bottle number of 1 was substantial or that a reduction in formaldehyde content by 25 percent was important and meaningful. For further details regarding the application of the U_s analysis to the catalytic and standard muffler, please refer to Section VII.

C. Correlation Studies

A study was made to determine, if possible, correlations between the odor panel responses and exhaust emissions. Recall that the odor panel measurements were made on separate days from the exhaust analysis. The first day of each inspection was devoted to sampling and analysis of the various exhaust emissions, followed on the second day by odor evaluation with the catalytic muffler. The catalytic muffler was removed and replaced by the stock muffler, and, on the third day, a repeat set of odor measurements was obtained. On the fourth day, the wet chemistry and physical measurements were repeated.

1. Description of Computer Program

The method of analysis selected for this correlation was a stepwise multiple linear regression program which computed all of the linear correlation coefficients. This program introduced variables into the regression equation such that the "most important" variable entered first. This technique was expected to be most helpful in determining what relationships (if any) exist between chemistry values and the odor panel responses. The computer program employed was an available linear stepwise multiple regression BM DO2R - version of June 2, 1964, from the Health Sciences Computing Facility, UCLA. Before discussing the results, however, it should be mentioned that the data input was not in log transformation form. The results, though valid, will generally be lower or more severe than the results might be if the data had been log transformed. Using the UCLA program, the odor and emissions measurements were studied by means of the Control Data Corporation (CDC) 3600 computer (Houston) through the data phone tie-in with SwRI, San Antonio.

2. Results

Initially, correlations were attempted for the "X"-1 muffler, operated in vehicle 681. The results of this correlation study, made with the three inspection tests performed after approximately 1, 2, and 3 months of vehicle operation, indicated no correlation existed between, for instance, "D" and each of the chemical constituents of interest such as aldehydes, formaldehyde, acrolein, SO_2, NO_x, and CO. This was also the case for the other four quality standards of "B," "O," "A," and "P." This generally negative result was not unexpected since the basic data acquired during the three weeks of testing with Bus 681 were found to be essentially the same.

Multiple regression statistical analyses were then performed on the data obtained with the Code "Y" catalytic muffler with Buses 678 and 768, both separately and together per the following schedule:

Case	Bus No.	Engine	Muffler	Data Input
I	678	E type	Code "Y" and stock	As-measured
II	678	E type	Code "Y" and stock	Emissions adjusted for inherent exhaust air dilution
III	678	E type	Code "Y" alone	As-measured
IV	678 and 768	E and N types	Code "Y" alone	As-measured

Of the above, the most informative and revealing computer study results were obtained with Case I for the as-measured data from Bus 678 powered by a Detroit Diesel 6V-71 E type two-cycle engine. The basic data on which this analysis was made may be found in Appendix E. Included as Appendix G are the computer printout sheets for Case I which exemplify typical analysis.

Shown on Table 44 is the list of twelve variables involved and their mean and standard deviation values. For each day of operation, three conditions were run in quadruplicate such that the idle, 20-mph cruise, and 40-mph data each represented eight data points for the "Y" plus the standard muffler. For purposes of computing the mean and standard deviation, for example, all of the "D" data were involved (twenty-four data points). Next, a correlation matrix was computed for the twelve variables, shown in Appendix G and reproduced in the text as Table 45. In discussing these correlation coefficients, it may be helpful to recall that the correlation coefficient is a measure of the strength of a linear relationship, and, in this particular case, we are generally concerned with a straight line relationship. From this table, excellent correlation may be noted for the "D" with the "B" odor data (0.903 correlation coefficient), total aliphatic aldehydes and acrolein (0.945 correlation coefficient), formaldehyde and total aldehydes (0.936 correlation coefficient), and NO_x with CO_2 (0.976 correlation coefficient). Sulfur dioxide did not appear to correlate well with any of the other variables except for possibly CO_2. Another way of considering the correlation coefficients is to summarize on the basis of odor qualities versus the selected chemical constituents known for their malodorous nature such as total aldehydes, formaldehyde and acrolein. Shown below is the approximate range of correlation coefficients determined versus "D," "B," "O," "A," and "P" on an as-measured data basis.

Odor Quality	Exhaust Emission	Correlation Coefficient
"D"	Acrolein, formaldehyde, total aldehydes	0.6 - 0.7
"B"	"	0.5 - 0.6
"O"	"	0.5 - 0.53
"A"	"	0.71 - 0.81
"P"	"	0.25 - 0.31 (inadequate)

TABLE 44. STATISTICAL CORRELATION STUDY OF DIESEL ODOR AND EMISSIONS LIST OF VARIABLES, THEIR MEAN AND STANDARD DEVIATION

Vehicle: Bus 678
Engine: Detroit Diesel 6V-71 E

Date: September 6 & 7, 1967
Fuel: EM-3A-F (No. 1 diesel)

Variable Number	Independent Variable	Mean	Standard Deviation
1	"D" Diesel composite, 1-12	5.55	0.86
2	"B" Burnt-Smoky, 1-4	1.64	0.35
3	"O" Oily, 1-4	1.48	0.39
4	"A" Aromatic-Aldehydic, 1-4	1.03	0.32
5	"P" Pungent, 1-4	1.05	0.34
6	Carbon monoxide, ppm	156.0	53.3
7	Carbon dioxide, %	3.41	2.03
8	Acrolein, ppm	3.74	2.97
9	Aliphatic aldehydes as ppm formaldehyde	24.89	14.28
10	Formaldehyde, ppm	15.51	8.14
11	Oxides of nitrogen, NO + NO_2 as ppm NO_2	352.0	216.0
12	Sulfur dioxide, ppm	0.69	0.48

Note: The above rounded-off from computer printout data presented in Appendix G to this report.

TABLE 45. STATISTICAL CORRELATION STUDY OF DIESEL ODOR AND EMISSIONS CORRELATION MATRIX

Vehicle: Bus 678
Engine: Detroit Diesel 6V-71 E

Date: September 6 & 7, 1967
Fuel: EM-3A-F (No. 1 diesel)

Variable Number	1 "D"	2 "B"	3 "O"	4 "A"	5 "P"	6 CO
1	1.000	0.903	0.795	0.793	0.670	0.155
2		1.000	0.771	0.746	0.527	-0.019
3			1.000	0.593	0.395	0.102
4				1.000	0.433	0.358
5					1.000	-0.148
6						1.000

Variable Number	7 CO_2	8 Acrolein	9 Aldehydes	10 Formal-dehyde	11 NO_x	12 SO_2
1	0.351	0.644	0.672	0.630	0.394	0.062
2	0.450	0.524	0.585	0.516	0.474	0.176
3	0.283	0.494	0.530	0.527	0.319	0.039
4	0.263	0.791	0.813	0.714	0.349	-0.063
5	0.078	0.303	0.294	0.225	0.106	-0.033
6	-0.122	0.598	0.558	0.631	-0.025	-0.198
7	1.000	0.224	0.068	0.077	0.976	0.760
8		1.000	0.945	0.877	0.321	-0.080
9			1.000	0.936	0.161	-0.164
10				1.000	0.161	-0.089
11					1.000	0.716
12						1.000

This may not be particularly significant compared to correlation coefficients normally obtained with engineering and scientific data. Considered in light of the subjective, qualitative, quantitative odor measurements and wet chemistry techniques involving colorimetric analyses, the correlation coefficients may not be unsatisfactory. What constitutes a satisfactory correlation coefficient, i.e., how far from a straight line the data can vary, has not been adequately established for these types of data, nor is there a known precedent that applies to the type of measurement systems employed.

Before discussing the results of the regression analysis, it may be helpful to describe the objective of the analysis and the end product. Without going into detail, the UCLA multiple linear regression identified the independent variable which permits the best fit for a particular dependent variable. This independent variable was then introduced into the regression analysis equation from which the regression coefficients were computed. From this, the best one independent variable model equation was established. Then, the second best independent variable was identified and introduced into the equation and new regression coefficients were computed. This procedure was continued stepwise until all variables were introduced unless the F statistic became meaningless, at which time the stepwise procedure stopped. The general regression analysis expression was of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 \ . \ . \ . + a_nX_n$$

where

Y - the dependent variable, one of the twelve variables of interest and for purposes of this analysis limited to "D," "B," "O," "A," or "P

a - a regression coefficient

X - the data point value on "as-measured" basis and not log transformed

n - at most the number of independent variables (limited to eleven in this study).

The end objective of the multiple linear regression analysis was to determine how well the regression or prediction fits the data and to identify relationships between the various odor qualities "D," "B," "O," "A," and "P," and the exhaust emissions including CO, CO_2, acrolein, total aldehydes, formaldehyde, NO_x and SO_2. In evaluating the computer printout results of Appendix G, two criteria of importance were a high multiple R value and a low standard error of estimation. To illustrate this process of identification, selection and the consequent regression equation, consider subproblem 1 in Appendix G in which the "D" ratings, variable number 1, was the dependent variable and the remaining variables considered stepwise. The pertinent results of each step of the analysis are summarized below:

Dependent Variable	Subproblem Number	Step Number	Independent Variable		Multiple R	Std. Error of Est.
			Number	Name		
1	1	1	9	Aldehydes	0.67	0.65
("D" Composite)		2	+7	CO_2	0.74	0.60
		3	+6	CO	0.77	0.59
		4	+12	SO_2	0.77	0.60
		5	+10	Formaldehyde	0.78	0.60
		6	+8	Acrolein	0.78	0.61
		7	+11	NO_x	0.78	0.64

Based on the criteria of highest multiple R value and low standard error of estimation, step 3 appeared to be the best fit and, from data in Appendix G, resulted in the following regression equation:

$$\text{"D"} = 4.63 - 0.004\, X_6 + 0.112X_7 + 0.048X_9$$

where

X_6 - CO reading in ppm

X_7 - CO_2 reading in percent

X_9 - total aldehydes reading as ppm formaldehyde.

The above illustrates a correlation of "D" with aldehydes, CO_2 and CO, but does not say whether the correlation was strong or weak. This is indicated by the multiple R values. If equal to 1, the correlation was the highest or strongest possible. The value of multiple R of 0.77 was adjudged to indicate a fair correlation as this value should normally be greater than 0.8. The strength of this correlation, however, should be considered in the light of the odor and emissions measurements methods involving psychological subjective responses and wet collected exhaust analyzed colorimetrically. In addition, use of log transformed data will tend to improve the multiple R value somewhat.

The next variable investigated was "B" which generally was the most obvious of the four qualities. Listed below is the step of the analysis which resulted in the best fit:

Dependent Variable	Subproblem Number	Step Number	Independent Variable Number	Independent Variable Name	Multiple R	Std. Error of Est.
"B" (Burnt-smoky)	2	4	6	CO	0.82	0.22
			7	CO_2		
			8	Acrolein		
			9	Aldehydes		

and

$$"B" = 1.12 - 0.002X_6 + 0.085X_7 - 0.095X_8 + 0.036X_9$$

where

X_6 - CO reading in ppm

X_7 - CO_2 reading in percent

X_8 - acrolein reading in ppm.

This correlation expression was judged satisfactory for multiple R of 0.82.

Shown below are the pertinent results of step 3 of subproblem 3 to relate the "O" oily quality with the exhaust emissions:

Dependent Variable	Subproblem Number	Step Number	Independent Variable Number	Independent Variable Name	Multiple R	Std. Error of Est.
"O" (Oily)	3	3	6	CO	0.61	0.33
			7	CO_2		
			9	Aldehydes		

and

$$"O" = 1.17 - 0.0017X_6 + 0.041X_7 + 0.018X_9$$

where

X_6 - CO reading in ppm

X_7 - CO_2 reading in percent

X_9 - aldehydes reading in ppm formaldehyde

Although the above was the best fit obtainable, the multiple R value of 0.61 was lower than desired, and the strength of the correlation was accordingly weak. The standard error of estimation was 0.33, and the standard deviation was 0.39 for the "O" reading (per previous Table 44) which means that the average "O" value was almost as good a predictor as the regression equation.

The aromatic-aldehydic quality "A" was then investigated to determine the best prediction of "A" in terms of the exhaust constituent data. Pertinent aspects of this correlation are shown below:

Dependent Variable	Subproblem Number	Step Number	Independent Variable		Multiple R	Std. Error of Est.
			Number	Name		
"A" (Aromatic-aldehydic)	4	3	9	Aldehydes	0.86	0.18
			11	NO_x		
			12	SO_2		

and

$$"A" = 0.535 + 0.016X_9 + 0.0006X_{11} - 0.1576X_{12}$$

where

X_9 - aldehyde reading in ppm formaldehyde

X_{11} - NO + NO_2 reading as ppm NO_2

X_{12} - SO_2 reading in ppm

The above regression equation indicates a fairly good correlation based on the multiple R value of 0.86. It should be noted that as an alternate, the independent variable X_9, aldehydes, resulted in nearly as good a fit when considered alone as shown in step 1 of subproblem 4 of Appendix G with a multiple R of 0.81 such that:

$$"A" = 0.58 + 0.018X_9$$

The above may be a preferred form since the SO_2 values appeared to contribute little toward improving the regression equation from step 3 of subproblem 4.

"P" was the last odor quality involved in the regression analysis as the dependent variable. The best fit occurred in step 2 of subproblem 5 is summarized as follows:

Dependent Variable	Subproblem Number	Step Number	Independent Variable		Multiple R	Std. Error of Est.
			Number	Name		
"P" (Pungent)	5	2	6	CO	0.51	0.30
			8	Acrolein		

and

$$"P" = 1.306 - 0.003X_6 + 0.069X_8$$

where

X_6 - CO reading in ppm

X_8 - acrolein reading in ppm

This regression equation lacks strength due to the low multiple R value of 0.51 and, similar to the "O" expression previously developed, the standard deviation for "P" was 0.34 versus the standard error of estimate of 0.30. Even though the equation lacks strength, it is interesting to note the appearance of acrolein in the "P" regression equation. There are some odor similiarities between the pungent standard and acrolein. The major perceived resemblance acrolein has to the "P" standard is the very strong and penetrating odor that each possesses. The "P"-4 standard has a penetrating quality from the acetic acid which burns the nostrils. Concentrated acetic acid, like acrolein, cannot be sniffed at close range. When sniffing acrolein, which is the stronger odor, and acetic acid together, the two odors were judged to be alike in their penetrating and burning characteristic.

3. Summary

It should be reemphasized that the judgement of the strength of various regression expressions was difficult to assess in light of the measurement methods of subjective odor and wet chemistry involved. In three of the five expressions developed, total aldehydes appeared in the correlation. That CO_2 appeared in the first three expressions indicates that, even though CO_2 is not odorous, it may be that CO_2 is correlated with a variable not currently measured. From a brief review of the correlation coefficients in Table 45, it may be noted that CO_2 and NO_x are highly correlated (correlation coefficient 0.976). From a combustion standpoint, this may be expected, i.e., for the diesel CO_2 may increase with an increase in fuel consumption as does NO_x to some extent. Incidentally, this may be why NO_x did not appear more often in the stepwise linear regression analysis. (The computer utilizes the lower subscript if the correlation coefficient equals 1.) NO_x could, if desired, be substituted for the CO_2 with suitable adjustment of the regression expressions because of the high correlation between CO_2 and NO_x. By deleting CO_2 from the computer input, NO_x would likely appear in the place of CO_2 in the regression equations. The computer correlation analysis conducted and described in this section appeared to have particular advantage in developing relationships between the diesel odor qualities and exhaust emissions. The experiments, data, and consequent correlation analysis conducted, however, should be considered preliminary, and subject to change and improvement. As mentioned earlier, the correlations are intended to be illustrative of the use of the stepwise regression method as a powerful tool in relating perceived subjective odor data to physical/chemical emissions measurements.

4. Description of Future Correlation Experiments

Based on the potentially useful correlations obtained with Bus 678 when operated with and without the "Y" muffler, it is suggested that future correlation studies be conducted with this particular vehicle using "Y" as a tool to obtain different exhaust emissions without having to change vehicles and engines. The "Y" muffler would be used as a matter of convenience and not for any other reason. After consideration of the practical aspects of operating a municipal bus with the ten-person odor panel, it is suggested that four operating conditions be investigated. The four operating conditions of interest include a 20-mph, 50-percent power cruise, a 30-mph, 50-percent power cruise, a 40-mph, 50-percent power cruise, and an idle after a 30-mph cruise. Conducting these four conditions in quadruplicate would result in sixteen runs which is, from a sampling and analysis standpoint, about the maximum number of runs that can be conducted in a normal working day. These four conditions would result in a variation of engine speed as the three cruise conditions range from around 900 rpm at 20 mph up to 1650 rpm at 40 mph. Associated with them are lower levels of exhaust air dilution than the large quantity of excess air handled during idle. The exhaust from the idle (approximately 600-rpm engine speed), on the other hand, even though highly air rich, contains substantial quantities of the exhaust constituents of interest.

The test scheme would involve operating on alternate days with the stock and "Y" mufflers. Over a period of 2 wk, 8 working days would be devoted to obtaining back-to-back data. Sampling for exhaust emissions, such as acrolein, formaldehyde, etc., would be conducted simultaneously with the odor evaluation to eliminate the possibility of there being a difference or inherent difficulty in correlation. It would be interesting to consider the effect of load at the two extreme cruise conditions, the 20-mph, 900-rpm engine speed cruise, and the 40-mph, 1650-rpm engine speed cruise. If zero and full load were considered at each of these speeds, this would result in four additional conditions and provide further information regarding the effect of fuel delivery and power on odor and other emissions.

Of particular interest in conducting the correlation studies would be the potentiality of the instrumental technique discussed in Section VIII. The correlation study should include analysis involving wet collected exhaust by gas liquid chromatography. Bag samples would be obtained during the 3-min period employed for exhaust sampling and odor evaluation. The bagged raw diesel exhaust would then be passed through suitable bubblers for absorption of most, if not all, of the odor constituents. This would permit the gas chromatograph analyses to be scheduled separately from operation of the vehicle, panel, and other chemical analysis. The bag sampling system appears to have particular merit in this regard.

XI. SUMMARY

The following is a brief summary of the pertinent results of the second year of research on odor, smoke, and other exhaust emissions from diesel powered vehicles.

(1) During the investigation of the effect of engine derating on odor and smoke, the following was found based on the single engine of each type employed. For the Detroit Diesel 6-71 N engine, it was noticed that derating had little effect on smoke or odor emissions. The lack of effect on smoke was attributed to the relatively low or light smoke level from the particular engine employed. Derating the Cummins NH-220 engine, however, reduced the measured smoke output, especially the initial step of engine derating, from 220 to 200 hp at rated speed. The derating to 180 from 200 hp was not as pronounced because of the relatively light smoke output obtained at 200 hp. As in Part I, derating had no noticeable effect on the perceived odor from this make of four-cycle engine. Similar derating experiments with a Mack END-673P powered tractor revealed the only instance in which power rating appeared to have a noticeable effect on odor. The exhaust odor from this four-cycle engine was slightly higher, generally speaking, than the other two engines investigated. Considering the qualities and their order of obviousness relative to other diesel exhausts evaluated, the improvement noticed with this particular Mack engine under the two constant speed conditions may not justify engine derating as a desirable technique. For derating to be useful and acceptable, it should be successful in most, if not all, conditions, not in one or two of the six investigated. The effect of derating on smoke was effective in reducing the visible emissions, as determined by the PHS smokemeter. This trend was in good agreement with that determined for the Cummins NH-220 engine and with previous experience. The effectiveness on smoke and general ineffectiveness on odor of diesel engine derating was demonstrated on three representative types of engines under identical operating conditions.

(2) The 6-month, five-truck fleet test of a diesel smoke suppressant fuel additive was, from a smoke reduction and performance standpoint, an unqualified success. This commercially available barium-containing additive reduced the visible smoke from one-half to as low as one-fourth the level measured with untreated number 2 diesel fuel. The effect of the smoke suppressant additive seemed greater under constant speed, maximum temperature operating conditions. For the 6-month test, including inspections at 0, 2, 4, and 6 months of operation, the additive seemed equally successful at the beginning, during and at the end of the test for each of the tractors investigated. Although the additive seemed to be more successful in certain tractors than in others, it did not seem dependent on the base smoke level. Care should be exercised in extrapolating the results of this test to other types of engines and vehicles or to other versions of the type of equipment used during this test.

(3) The DEOX system of Diesel Exhaust Manifold Oxidation appeared to have only a partial effect on odor. Although some reductions were measured under the 20-mph cruise and idle conditions, these reductions do not justify the present DEOX system for further consideration. In light of the partial reductions obtained, the DEOX system can be classified as a limited technical success. Acceleration after idle, the 40-mph cruise, and the deceleration condition were also important modes representative of actual municipal bus operation, and DEOX lacked positive reduction during these modes. No positive reduction in smoke was obtained with or without the DEOX system operative.

(4) Two back-to-back odor evaluations were performed with the Jacobs engine brake operative and disconnected. Little beneficial effect on diesel odor was noticed. Only during the final evaluation did the Jacobs brake appear to have a slight, though almost negligible, effect on exhaust smoke. It appears that the Jacobs engine brake is effective as a vehicle retarder but had an insignificant effect on odor and smoke from the particular N series, two-valve, Detroit Diesel 6V-71 engine investigated.

(5) An evaluation of two available exhaust catalytic devices coded "X" and "Y" installed on municipal buses revealed that one device noticeably reduced exhaust odor and other emissions such as formaldehyde, total aldehydes and acrolein. The three similar "X" devices were inspected on eight occasions with the two vehicles identified as nearest the mean of the ten vehicles evaluated during Part I. A third vehicle powered by the newer N type engine was also employed. As a result, the "X" mufflers were found to be effective in changing or reducing the vehicle exhaust odor under only some operating conditions and during some inspections. The "X" mufflers inconsistently reduced odor under two of the five conditions employed. None of the three "X" devices had a consistently beneficial effect on vehicle exhaust smoke. Exhaust emissions data, for the "X" mufflers, likewise failed to indicate any consistently affected parameter. During the two "Y" muffler inspections, this device reduced odor and certain of the exhaust emissions. The "Y" muffler, however, had no beneficial effect on smoke and, in some instances, resulted in slightly higher smoke readings. The results of the odor evaluations indicated fairly consistent reductions in odor under four out of five conditions. These favorable reductions, identified as statistically different, reveal the relative effectiveness of the "Y" muffler. The reductions were found to be greater with the bus powered by the E type engine bus. Consistent reductions were also found in the exhaust emissions, such as acrolein, aldehydes and formaldehyde. Gross changes in exhaust emissions were found for the "Y" equipped E powered bus and slight changes were found for the "Y" equipped N type engine. Finally, the operation of all the catalytic mufflers, temperatures, pressures, and other performance appeared normal.

(6) In summary of the chemistry support portion of the program, procedures were established and analytical methods adapted to permit routine measurement of CO, CO_2, acrolein, total aliphatic aldehydes, oxides of nitrogen, formaldehyde, oxygen, and sulfur dioxide. These measurements provided needed support during the catalytic muffler evaluations and the Flxible Coach base line data acquisition. The preliminary feasibility study of an instrumental odor method for possible correlation with the human odor panel was the most challenging, yet important, aspect of this phase. The objective was to determine and conduct limited experiments of a practical, simple method for correlation with the odor panel. Gas-liquid chromatography was initially selected as the best method for separation and consequent detection with the majority of the experimental effort centered about this type of instrument. Difficulties normally encountered with diesel exhaust sampling and preparation, including preseparation of components prior to injection, were reduced by use of water collected diesel exhaust odor. Bubbling raw two- or four-cycle diesel exhaust slowly through water removed most, if not all, of the perceptible odor. The search for a suitable GC column and column conditions identified several candidate materials which may separate the mostly polar materials in the water absorbed diesel odor. A suitable program, including the human odor ratings and other emissions measurements, was developed for statistical correlation.

(7) A limited study of the effect of exhaust pipe size (exhaust velocity) on smoke readings by the PHS smokemeter was conducted at special request. The results indicated that pipe size and exhaust flow normally encountered with the multicylinder, four-cycle engine investigated had no effect on smoke reading. As pipe size was increased (exhaust velocity decreased), the readings under equivalent smoke production conditions increased, particularly at the higher smoke levels investigated.

(8) At special request, a variety of tractors and engine driveline configurations, including turbocharged engines, was studied with a tentative smoke test procedure. Of necessity, these experiments were conducted with rental or locally available truck-tractors operated on a chassis dynamometer. Both the quasi-constant speed (lugging) and acceleration from idle conditions were investigated using a suitable strip chart recorder to continuously record the PHS smokemeter indication versus time. Vehicle speed and engine speed were also monitored. The greatest difficulty found was with the acceleration from idle procedure, possibly due to the test equipment utilized.

(9) An unsuccessful attempt was made to evaluate the prototype Gordine diesel electrostatic precipitator. This evaluation, with the exhaust from a test bed operated, six-cylinder, four-cycle truck-tractor diesel engine, resulted in premature failure of various components of the device. These failures, mostly structural and mechanical, occurred during the first 5 min of operation and prior to being able to turn "on" the power supply. Therefore, the potentialities of the device for removal or reduction of exhaust smoke were not determined.

(10) Previous odor and smoke data from municipal buses have been obtained exclusively with a popularly used two-cycle powered bus. Availability of a four-cycle powered Flxible transit coach permitted base line data of odor, smoke, and other exhaust emissions such as CO, CO_2, acrolein, formaldehyde, NO_x, total aldehydes, and SO_2 to be obtained. The engine-transmission-rear axle configuration of the Flxible coach allowed use of operating conditions for odor, smoke and emissions measurements without change. Therefore, the base line data acquired with the one Flxible unit may be compared with other vehicles evaluated under the same conditions. The conditions for emissions were expanded to include cruises at 30 mph (40 hp) and 25 and 50 mph at no load and full load.

(11) In summary of the statistical support portion of the program, several important items were achieved. The first was justification of simple arithmetic averaging of the human odor panel responses. Next, a suitable nonparametric statistical test was selected and employed to analyze the back-to-back catalytic-stock muffler evaluation data for differences. Last, a multiple linear regression analysis was employed to investigate and develop regression equations to correlate odor data in terms of "D," "B," "O," "A," and "P" ratings to CO, CO_2, acrolein, aldehydes, formaldehyde, NO_x, SO_2, etc. Satisfactory expressions were developed for the "D," "B," and "A" odor ratings for the best case studied. An improved correlation program, which could include an instrumental technique for odor measurement, was formulated.

XII. CONCLUSIONS AND RECOMMENDATIONS

Based on the work performed during this program, the following conclusions and recommendations are offered for consideration. Conclusions and recommendations as a direct result of the Part II program are listed first, followed by general observations and long-range recommendations which appear warranted.

(1) Of the two types of municipal bus type catalytic mufflers evaluated, the "Y" unit appeared to have the greatest effect on odor and exhaust emissions. This conclusion was based on single back-to-back evaluations in two different two-cycle powered municipal buses after a minimal mileage accumulation with a single "Y" type exhaust system. It is recommended that a long-range fleet test of a number of similar "Y" units be conducted in which the odor and other emissions are measured back-to-back at the beginning, midway, and at the end. Such a fleet test conducted under routine municipal bus operation should also include a determination of maintenance, operating, and installation costs to establish the cost effectiveness of the device. Although the "Y" muffler system had an excessive sound level, it may be possible to match the reactors with a suitable silencer without excessive exhaust backpressure. As additional devices are available, they should be considered for possible screening and, if warranted, fleet tested.

(2) The fleet test of a commercial smoke suppressant additive was successful in confirming the effect of the material in reducing visible smoke emissions. Although additional fleet tests of smoke additives in intercity trucks do not seem necessary in the near future, fleet tests of other types of diesel fuel additives are suggested. A number of commercially available, odor modifying fuel additives are claimed to either change, mask, perfume, alter or otherwise improve the odor from certain diesel powered vehicles. A few odor and smoke combination additive packages are also either available or are being developed. A long-range test of a diesel fuel odor or odor-smoke additive in a fleet of two-cycle powered municipal buses is recommended to establish the potentialities for odor or odor-smoke reduction by this method. Although evaluation of candidate odor additives was not included in either Part I or Part II, guidance in additive selection may be available from other PHS programs. Because of the increasing number of available diesel fuel additives, it may be desired to conduct additional screening tests prior to the selection of the odor or odor-smoke additive for the recommended fleet test. In addition to determining the performance at the initiation, midway, and at the completion of this fleet test, sufficient cost data should be obtained to establish the cost effectiveness of odor and/or smoke reduction by this method.

(3) Diesel engine power and torque derating has been demonstrated to be successful in significantly reducing the visible smoke emissions from the representative two-cycle and four-cycle engines investigated. The effect of derating on odor was of little or no significance for the particular engines involved under most conditions investigated. For new equipment, the use of engine derating for smoke reduction should be considered with the potentialities available with combustion chamber, fuel delivery, and other design improvements. For diesel powered vehicles already in service, derating as a smoke reduction method should be considered with alternatives such as additives, altered maintenance procedures, driver habits, and route and vehicle loadings-speeds, among others. These alternatives should be studied for the type of diesel powered vehicle service application, engine-vehicle configuration and engine capabilities on a cost effectiveness basis. No additional studies of engine derating are recommended at this time.

(4) The lack of consistent and significant odor and smoke improvements by use of the Jacobs brake, an engine device for braking the vehicle, tends to eliminate this device for odor and/or smoke reduction with two-cycle powered municipal coaches. Apparently, reports of the beneficial effect of the Jacobs brake on odor and smoke were based on the improved cleanliness and breathing of the induction and exhaust systems sometimes noticed with the older, four-valve, two-cycle engines.

(5) Investigations of exhaust dilution via the "DEOX" system, the addition of fresh outside air to the underside of each engine exhaust valve of a two-cycle powered city bus failed to show a consistent or substantial improvement in odor or smoke. Accordingly, no further research with "DEOX" in its present configuration is recommended. The method may deserve further study for use with systems such as insulated or heated exhaust manifolds, piping, etc., and may have potential for possible odor or smoke reduction if a gas other than air is injected.

(6) The sampling and analysis systems for emissions other than odor and smoke were successfully employed and warrant further application to diesel exhaust. The routine measurement of CO, CO_2, acrolein, formaldehyde, total aliphatic aldehydes, NO_x, and SO_2 must be expanded, however, to include total unburned hydrocarbons. The expected availability of a suitable high-temperature hydrogen flame ionization instrument should permit satisfactory measurement of this important emission. Other diesel exhaust constituents including, for example, carbonyls and polynuclear aromatics such as benzpyrene are suggested for measurement on a selected basis.

(7) The gas liquid chromatograph analysis of a wet collected sample of diesel exhaust odor represents a potentially simple method for measuring diesel exhaust odor. Although this technique has a number of distinct advantages, a substantial level of effort will be needed to develop the reliability, repeatability, and, most important, its correlation with the subjective qualitative-quantitative ratings of the human odor panel. To do this, a number of fuels, operating conditions, vehicles, and engines will ultimately be involved along with extensive statistical analysis. A suitable instrument method, correlatable with the odor panel, is the greatest need before widespread exhaust odor research and control is possible.

(8) Application of statistics to the Part II results was dependent on the odor panel response treatment method employed. Justification and adoption of simple arithmetic methods by which the odor panel was treated as a single entity was an important milestone. A statistical technique involving the nonparametric Mann-Whitney "U" test for statistical difference was useful for treatment of odor and exhaust emissions data from back-to-back device evaluations. Additionally, a multiple linear regression computer analysis appeared to be particularly successful in relating odor and exhaust emissions data. These statistical techniques and data treatment methods are recommended for use in the future.

(9) The limited investigation of exhaust pipe diameter (exhaust velocity) on smoke reading revealed pipe size did not affect the indication for normally used pipe sizes (exhaust flows). Additional studies are suggested to confirm and explain the reason the smoke readings obtained with larger (slower exhaust velocity) pipes than usual resulted in higher readings, especially under heavy smoke conditions.

(10) Preliminary studies with the tentative PHS smoke test method revealed that the procedure or a modified similar procedure could be employed to measure smoke tendencies of diesel engines or diesel powered vehicles. Additional studies appear justified to explore the utility of the continuous smoke trace specified and to establish the applicability of this measurement system to different types of equipment on a variety of chassis and stationary dynamometer test machines. Concurrent with these recommended studies, continued development and proof test of the PHS smokemeter--continuous recorder system under transient conditions--should be included. The preliminary tests illustrated the great variety of different two- and four-cycle engines and engine versions, transmissions, and rear axle arrangements that are in routine use in intercity truck-tractors. Accordingly, additional studies in depth, including exhaust odor evaluation, are recommended with other typical truck-tractors with different transmission and rear axle drivelines. More data on smoke and odor may be warranted with the turbocharged diesel, relatively unstudied to date.

(11) The base line odor, smoke, and exhaust emissions acquired with the four-cycle powered Flxible Coach may be directly compared to similarly obtained municipal bus data. It is recommended that, as new engine-vehicle mass transportation units become available,

similar data should be obtained. For example, little emissions data are available for gas turbine powered urban-suburban transit coaches or intercity truck-tractors.

(12) The attempt to evaluate the smoke reduction effectiveness of the Gordine diesel electrostatic precipitator was unsuccessful due to premature mechanical and structural failure. It is recommended that a circular cross-sectional design be considered of at least 1/16-in. thick steel construction instead of the light gage sheet metal rectangular cross-sectional prototype. The copper collector screen should be securely fastened within the precipitator. The electrodes utilized to charge the particles should be securely fastened and, if possible, relocated to reduce the power breakdown to the housing experienced. These minimum changes should be effected prior to reattempting a performance evaluation.

In addition to the aforementioned conclusions and recommendations made as a result of this program, other needs have become evident. The odor data obtained to date have been in terms of odor qualities and intensities per the PHS Q/I kit and smoke density or opacity per the PHS smokemeter. Eventually, this and future similar data should be related to what the general public feels and says regarding diesel powered vehicle odor and smoke. To relate the laboratory measurements to the general public reactions, comprehensive field surveys are recommended. These surveys should have as their objective the determination of public opinion to various levels of diesel exhaust odor and smoke under simulated realistic conditions. The surveys should involve a statistically significant number of participants from a number of cities across the United States.

Finally, not enough is known about the toxic properties and subsequent effects of diesel exhaust on human health and property. Odor and smoke, two noticeable emissions from some diesel powered vehicles, are widely thought of as nuisance emissions. Certain control methods proposed for reduction of smoke and/or odor involve fuel alteration or fuel additives. For example, barium-containing smoke suppressant additives are currently used in certain locales without complete knowledge of their products of combustion and their effect, both short- and long-term, on human health. During visits by medically oriented researchers, they have made repeated statements of the potentially deleterious mechanism by which the smoke particulates or aerosols, acting as carriers, can penetrate the olfactory and upper respiratory area and gain access to the lungs. The materials carried by these particles and aerosols and their consequent effects on health have yet to be completely established. A proposed method to gain additional knowledge in this area would be to conduct long-range, side by side studies of air plus diesel exhaust versus air alone, or exhaust from a diesel operating on fuel with and without additive, etc., using various plants and animals as test specimens. To conduct such side by side studies would involve large "greenhouse" type enclosures identically exposed to sunlight and other climatological factors but such that the exhaust dilution and other parameters could be controlled. This and other studies suggested in this section would greatly enhance and extend the usefulness to the U. S. Public Health Service of the laboratory odor and smoke data determined during this and future similar programs.

LIST OF REFERENCES

1. Springer, Karl J., "An Investigation of Diesel Powered Vehicle Odor and Smoke - Part I," Final Report to the U. S. Public Health Service, Contract PH 86-66-93, March 1967.

2. Springer, Karl J., and Stahman, Ralph C., "An Investigation of Diesel Powered Vehicle Odor and Smoke," National Petroleum Refiners Association Paper No. FL 66-46, September 15-16, 1966.

3. Turk, Amos, "The Selection and Training of Judges for the Sensory Evaluation of Odor Intensity and Character of Diesel Exhaust," PHS Publication No. 999-AP-32, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio.

4. Miller, C. O., "Diesel Smoke Suppression by Fuel Additive Treatment," SAE Paper No. 670093.

5. Cummins, C. Lyle, and Haviland, G. C., "The Jacobs Engine Brake - A New Concept in Vehicle Retarders," SAE Paper No. 387A presented at the National West Coast Meeting, Portland, Oregon, August 1961.

6. Reckner, Louis R., "Final Report on Diesel Exhaust - Composition, Odor and Eye Irritation," prepared for U. S. Public Health Service (Contract PH 86-66-91) and Coordinating Research Council, Inc., (CRC Project No. CD-9-61), June 12, 1967.

7. Hurn, R. W., and Seisinger, D. E., "Air Pollutant Inventory - Enter the Diesel," Presented at the API Division of Refining Meeting, Montreal, Canada, May 1965.

8. Cohen, I. R., and Altshuller, A. P., "A New Spectrophotometric Method for the Determination of Acrolein in Combustion Gases and in the Atmosphere," Anal. Chem., 33, pp. 726-33 (1961).

9. Cohen, S. R., and Saltzman, B. E., "Determination of Acrolein: 4-Hexylresorcinol Method," Selected Methods for the Measurement of Air Pollutants, 999-AP-11, p. G-1, May 1965.

10. Sawicki, E., et al., "The 3-Methyl-2-benzothiazolone Hydrazone Test," Anal. Chem., 33, pp. 93-96 (1961).

11. Hausen, T. R., "Determination of Aliphatic Aldehydes: 3-Methyl-2-benzothiazolone Hydrazone Hydrochloride Selected Methods," Anal. Chem., 33, p. F-1 (1961).

12. CRC Report of Scott Research Laboratories, "Diesel Exhaust Composition and Odor: Progress Report for Year 1965," p. 5, October 1966.

13. Siggia, S., Quantitative Organic Analysis via Functional Groups, John Wiley, 3rd edition, pp. 124-128 (1964).

14. Reckner, L., et al., "The Composition and Odor of Diesel Exhaust," Proc. American Petroleum Inst., 45, pp. 133, 141 (1965).

15. Saltzman, B. E., "Colorimetric Microdetermination of Nitrogen Dioxide in the Atmosphere," Anal. Chem., 26, 1949-55 (1954). Scott Laboratories Adaptation.

16. Hochheiser, S., "Determination of Sulfur Dioxide: West and Gaeke Method," Selected Methods for the Measurement of Air Pollutants, 999-AP-11, p. A-1, May 1965.

17. Springer, Karl J., "Investigation of the Effect of Exhaust Pipe Diameter and Exhaust Velocity on Smoke Readings Using a Full-Flow Light-Extinction PHS Smokemeter, per Request of October 20, 1967, with Stationary Operated, Naturally Aspirated Engine," Special Status Report to U. S. Public Health Service, Contract PH 86-67-72, October 30, 1967.

18. Springer, Karl J., "Preliminary Smoke Data per Requests of October 12 and October 20, 1967, with Turbocharged and Naturally Aspirated Diesel Engines," Special Status Report to U. S. Public Health Service, Contract PH 86-67-72, November 1, 1967.

19. Brubacher, M. L., "California's Program to Reduce Diesel Smoke," SAE Paper No. 660548 presented at the National West Coast Meeting, Los Angeles, California, August 8-11, 1966.

APPENDIXES

A. Engine Derating Results
B. Results of a Fleet Test of a Smoke Suppressant Additive
C. Results of Investigation of the Effect of Diesel Exhaust Manifold Oxidation (DEOX) on Odor and Smoke from a Two-Cycle Diesel Powered Municipal Bus
D. Results of Investigation of the Effect of the Jacobs Engine Brake on Odor and Smoke Emissions from a Two-Cycle Diesel Powered Municipal Bus
E. Catalytic Muffler Evaluation Results
F. Smoke, Odor, and Other Emissions Measurements Obtained for Various Limited Studies and Investigations under Phase G
G. Results of Linear Stepwise Multiple Regression Analysis of Odor and Exhaust Emissions Data Obtained with a Municipal Bus Powered by a Two-Cycle Engine

Copies of the Appendixes
were included in the fifty
"book-bind" copies only.

Preceding page blank